Strapdown Inertial Navigation Systems

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Introduction

In many modern aircraft, like multi-rotor UAVs or drones, flight navigation and control is critical for maintaining safe and stable flight. One major way navigation is done on UAVs is with a strapdown inertial navigation system (INS). With the miniaturization of on-board electronics, the processing power and hardware required to implement a strapdown INS has become smaller and more affordable, to the point where many affordable recreational drones use strapdown INS technology for flight navigation and control.

Strapdown Inertial Navigation System

A strapdown INS is mainly comprised of three accelerometers and gyroscopes attached to the aircraft. Each accelerometer measures the motion of the aircraft in three directions of travel, while the three gyroscopes are used to obtain information about the direction the aircraft is facing. With the information from these sensors, the heading, speed and position of the aircraft can be computed. See figure 1 for the layout of a typical strapdown INS system. Compared to a traditional gimballed navigation system, a strapdown INS significantly reduces cost and size of the system, and doesn't require any external inputs or devices. However, due to errors in manufacturing and propagation errors in the on-board calculations, a strapdown INS can have significant error, especially in low-cost systems.

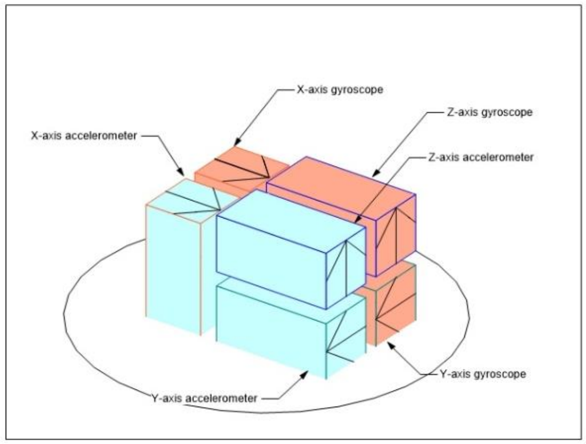

Figure 1. Layout of a typical strapdown INS – blue sensors and accelerometers and red sensors are gyroscopes.

Due to these issues, different compensation and calibration methods need to be used to correct errors caused by sensor and computation biases.

Self-Alignment

Before flight, a strapdown inertial navigation system must be calibrated, or aligned, to take accurate navigation measurements. One method of self-alignment is to physically shift and rotate the INS before takeoff [3], however this may be expensive and impractical due to space and weight limitations. Another method is the determine the orientation of the platform analytically. Using data collected from sensors prior to takeoff, measurements of its current heading are made and compared with predefined values of Earth's gravity and rotation [6].

This alignment method be easily implemented with existing onboard computers, but requires very precise gyroscopes and accelerometers. Due to the prohibitive cost of high quality sensors, alignment of strapdown inertial navigation systems is usually done using external navigation systems, such as a GPS, to reduce cost and complexity in UAVs.

Error Correction Techniques

Correcting Gyroscope Errors

One issue with low-cost strapdown INS systems is that measurements obtained from gyroscopes may not produce an accurate heading, especially during sharp turns and rotations as demonstrated in a report by NASA [2]. This is due to the high centrifugal forces acting on the gyroscopes during fast and sudden movements. As seen in the report, unfiltered attitude measurements from the strapdown INS during test flights deviated from the control results obtained from a differential GPS system during fast and sharp motion. One affordable method used to compensate for this error is to apply computational filters, such as the Extended Kalman Filter (EKF) or a Complementary Filter. The EKF reduces errors by fitting non-linear measurement data to a pre-determined linear model, while the Complementary Filter reduces noise and unwanted data. The corrected INS measurements obtained from applying the filters were similar to the results obtained from the control measurements, showing how filtering strapdown INS measurements can significantly improve the accuracy of attitude measurements.

Long Term Drifts and Biases

Another source of error is bias and drift caused by sensor data over very long flights. This long-term drift is due to small error biases in the inertial sensors that get amplified over extended periods of time without continuous calibration. One way to compensate for this error is to implement a rotation auto-compensating system on the strapdown inertial navigation system [8]. This method is implemented by placing the INS on a rotating platform. If the strapdown INS is rotated at a constant rate, the report demonstrates how errors caused by long-term sensor drift and bias in the directions parallel with the rotating platform fall into a periodic pattern and can be easily removed. Even though rotation of the INS is not feasible on small UAVs, this rotation auto-compensation method can significantly improve the long-term accuracy of a strapdown INS on larger aircraft where a rotating INS platform is feasible.

Incorporating External Devices

In some strapdown INS systems, the use of compensation and alignment techniques mentioned above are not feasible in small low cost UAVs due to size, weight, or cost restrictions. In these cases, external systems are often used in conjunction with the strapdown INS to increase the accuracy of the navigation system.

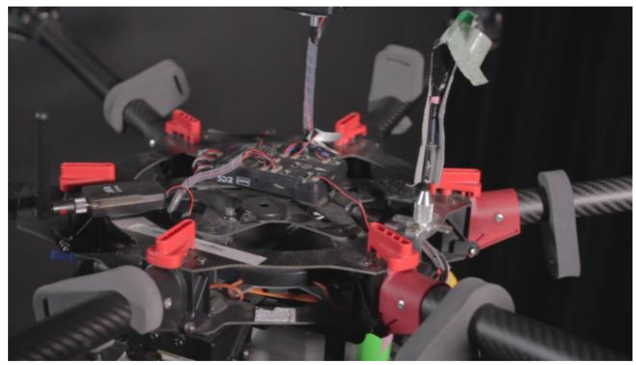

Figure 2. GPS and telemetry on the Blue Team's DJI-900 UAV.

Differential GPS System

One of the most common methods to increase accuracy is incorporating a GPS navigation system with the INS, due to the widespread adoption of GPS and its low cost. To further increase the accuracy of GPS signals, differential GPS systems are implemented, which uses the difference in GPS coordinates between the aircraft and a fixed base station to calculate the precise position of the UAV. This differential GPS system significantly increases the accuracy of the navigation system [7], but requires clear reception from GPS satellites, which may not be available if the UAV is flown indoors or in dense urban areas.

Sensors and Other Devices

Apart from GPS, other sensors and devices can be used to increase the accuracy of the navigation system. Measurements from various sensors, such as barometric altimeters or ultrasonic sensors, can help provide accurate altitude measurements. Radar systems, such as a synthetic aperture radar (SAR) system, can also be used to obtain accurate height and velocity measurements by analyzing pulses sent and received by the radar [4]. When used in conjunction with the strapdown INS, these integrated systems provide more accurate navigation measurements while eliminating the need for external inputs.

Conclusion

With the reduction in size and cost of gyroscopes and accelerometers, as well as the increased processing power of on-board computers, the use of strapdown inertial navigation systems have become more widespread in UAVs and other aircraft. In some cases, strapdown INS have even replaced large and expensive gimballed navigation systems. Due to the errors and biases in the INS, measurements from a strapdown INS may not provide the accuracy required, leading to the use of a variety of mechanical and analytical correction techniques, as well as the need for accurate self-alignment before flight. In addition, a strapdown INS can be used in conjunction with other sensors or systems, such as with differential GPS or other sensors to further increase accuracy. Even though additional hardware and computing power may be needed to obtain accurate navigation measurements, the significant reduction in cost and size make the strapdown inertial navigation system one of the leading navigation systems in low-cost UAV and aircraft today.

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