**Abstract**

This study proposes a method to improve the accuracy of attitude estimation of an ultra low-grade inertial navigation system (INS) by integration of a GPS receiver and smart placement of the GPS antenna. The proposed method utilizes the "lever arm effect" originating from the difference in the locations of the inertial measurement unit (IMU) of the INS and the GPS antenna. The method enhances the observability of the attitude, which can neither be correctly estimated by such a low-grade IMU nor be derived directly from the GPS receiver's measurement values, and its advantage is shown experimentally with a prototype system. Furthermore, analysis of covariances matrices reveals further hints to use the method effectively.

**Lever arm effect**

If the GPS antenna is fixed at the location different from the IMU, the linearized observation equation of Kalman filtering is derived as follows:

\[
\mathbf{x}_k = \mathbf{F}_k \mathbf{x}_{k-1} + \mathbf{w}_k
\]

where \(x, x, a, \) and \(b\) stand for velocity, position, attitude, and sensor biases respectively, and \(x\) and \(a\) indicate a non-zero value and the error of observed value. This equation shows that the outputs of a GPS receiver include clues of the attitude indirectly, and can be used to help the estimation. This is "lever arm effect".

**Experiment results (1)**

In all cases, the outputs of the prototype system do not diverge and are nearly equal to those of GAIA. A comparison of the time history between the case (C) of the prototype and GAIA is shown below.

**Covariance matrix analysis**

The system covariance matrix of Kalman filtering contains information on how accurate and correlate the estimated values are, when the optimal estimation is conducted. If the proposed method is effective, the part of the matrix related to the attitude should have smaller variances, which means it has the possibility of the estimation being more accurate. It should also have stronger dependencies to other parts, which indicates that there are more hints.

In case (C), the variances are the smallest and the deviances are the strongest among all cases. In case (B), those values are smaller and stronger than in case (A). However, the difference between the two is slight.

**Experiment with a prototype system**

To evaluate the effectiveness of the proposed method, experiments to compare the flight log obtained by a prototype system with that of a high-precision INS/GPS system, GAIA, are performed.

**Introduction**

Navigation instruments should be smaller, lighter, and more cost-effective. Not only for conventional aerospace field, but also for applications such as small unmanned aerial vehicles, and car navigation.

The integration of an ultra low-grade INS which consists of micro-electro-mechanical system (MEMS) inertial sensors and civil-use GPS receiver is one of the best solutions.

Kalman filtering compensates for the low accuracy of MEMS inertial sensors. However, the accuracy in attitude, especially heading, is not sufficient, and should be improved. According to the author's previous study, the error in heading is about 10 degrees.

**Discussion**

The proposed method is effective, because the attitude accuracy, especially in heading, is improved. It is also worth to stress that even though the outputs of the GPS receiver are not accurate for the attitude determination, the standard deviation of the attitude error is settled to only 3 degrees in case (C).

The covariance analysis supports the fact that case (C) is the most effective. However, it cannot explain the difference between cases (A) and (B) clearly. This would be due to the poor accuracy of the MEMS gyros, because the "lever arm effect" utilizes the angular velocity sensed by the MEMS gyros. On the other hand, in case (C), that disadvantage is overcome by its 5 degree of freedom, which is larger than the 3 degrees in cases (A) and (B).

Without changing the MEMS gyros, the further improvement will be achieved by 1) using the longer arm, and 2) using more gyros.

**Conclusion**

This study proposed a method to improve the attitude accuracy of an ultra low-grade INS by utilizing GPS antenna placement, and comparison experiments showed its effectiveness. The covariance analysis revealed that the poor accuracy of the MEMS gyro degraded the performance of the proposed method.