Flight Test Results of GPS/INS Navigation Loop for an Autonomous Unmanned Aerial Vehicle (UAV)

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BIOGRAPHY

Mr. Jong-Hyuk is a PhD candidate at the Australian Centre for Field Robotics (ACFR), the University of Sydney. He received his Bachelor of Science in Electrical Engineering in 1997 and Master of Science degree on GPS/INS integrated system in Electrical Engineering from the Chungnam National University, Korea in 1999. He worked for Navicom Ltd. in Korea as a GPS engineer for one year where he designed GPS hardware and firmware. His research interests are in integrated navigation system, non-linear estimation, attitude GPS system, and simultaneous navigation and map building.

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ABSTRACTS

This paper presents the real-time flight test results of a GPS/INS navigation system for an Autonomous Unmanned Aerial Vehicle (UAV). The GPS/INS system was developed as a part of the Autonomous Navigation and Sensing Environment Research (ANSER) program between the University of Sydney and BAE Systems [1]. The system was designed as loosely coupled integration architecture. The system was installed and tested on the UAV, Brumby-MK3 developed by the University of Sydney. The flight test results showed that the GPS/INS navigation system worked properly in real-time operation and could provide accurate navigation solutions under high dynamic and high maneuvering environments.

INTRODUCTION

The UAV usually has limited payload capacity and sometimes requires high manoeuvrability to meet specific missions as well as precise navigation systems for autonomous flight operation. To meet these requirements, a GPS/INS integrated system equipped with a small and light, or equivalently low-quality, IMU was implemented.

The GPS/IMU integration system has been a hot research area over past decades and successfully applied to many military areas. The integration approach can be roughly divided into loosely coupled and tightly coupled, depending on the degree of coupling [2]. The trend nowadays has been toward the deeper levels of integration where INS aiding can reduce the GPS tracking loop bandwidth or reduce the integer ambiguity search volume with attitude determination systems to achieve more optimal performance [2]. In this application, the loosely coupled structure was used with GPS position aiding. The benefits of loosely coupled integration is that it treats the GPS and INS as independent systems, so various kinds of off-the-shelf products can be used for integration purposes as well as standalone functionality which provides more flexibility than tightly coupled systems. The main disadvantages of this structure are that it is suboptimal and if the number of satellites is less than four, the system navigates based on pure inertial solution alone.

The GPS/IMU system was implemented inside the Flight Control Computer (FCC) and it plays a pivotal role in the UAV within the ANSER project. It should provide reliable high frequency navigation solutions to the flight controller, to other sensor nodes, and also provide precise synchronization between on-board systems and multiple vehicles.

The developed GPS/IMU system consists of an IMU, two GPS receivers, and tilt sensors. A light and low grade IMU is used which has bias repeatability of 0.01deg/s and 1mg for the gyros and accelerometers

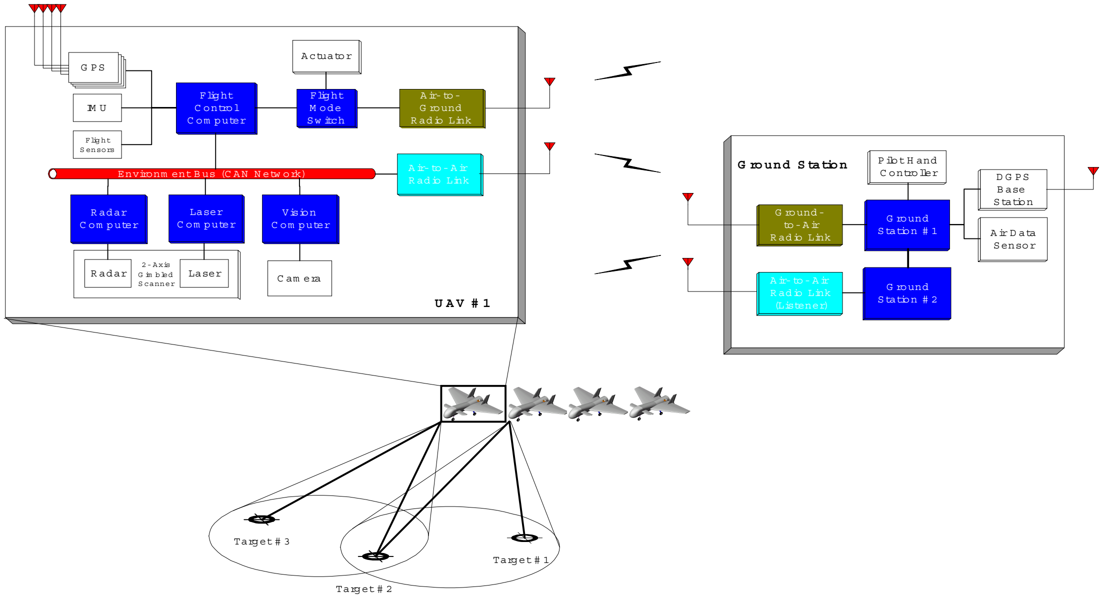

Figure 1 The ANSER project for Decentralized Data Fusion in multiple UAVs.

respectively. The gyros cannot detect the earth rotational rate due to their low resolution. Two GPS antennas were installed on the wings of the UAV to incorporate GPS attitude information. The master GPS provides a navigation solution to the GPS/IMU filter. The carrier phase measurement data double differenced with the slave GPS is used to get attitude information. Prior to obtaining the GPS attitude information, the integer ambiguity on the double differenced carrier phase measurement is resolved. The LAMBDA method [3][4] and constraint ambiguity search algorithm [5] were tested but the result is not presented in this paper. Two inclinometers are used to calibrate the accelerometers during the initialisation stage and provide the angle accuracy after the flight test. Due to the highly dynamic nature of the UAV, the lever-arm effects are not negligible, so the sensor offsets of the IMU and GPS antenna were measured precisely and compensated before fusing the data.

This paper, will first briefly describe the ANSER project. Secondly, the implemented GPS/IMU navigation loop will be discussed in detail. Thirdly, two flight test results will be presented, and finally, the conclusions and future plan will be presented.

THE ANSER PROJECT

The ANSER project is a joint research program between the University of Sydney and BAE Systems. The main goals of this project are to demonstrate Decentralized Data Fusion for Picture Compilation (DDF/PC) and Decentralized Data Fusion for Simultaneous Localisation and Map Building (DDF/SLAM) across multiple UAV platforms [1].

The system can be divided into four categories; multiple flight vehicles, on-board systems, communication links, and ground station. The flight platform is a Brumby-MK3 as shown in Figure 2, which has a 20kg payload capacity, 45min flight duration, and 100knots maximum speed. The on-board system consists of flight control computer, GPS/IMU fusion filter, vision system, radar/laser system with gimballed scanner, and flight electronics. The vision and radar system perform target-tracking, target registration and decentralized data fusion. The air-to-air communication links are established for the decentralized fusion network and the air-to-ground link is used for pilot control, differential GPS correction, and monitoring vehicle status. The ground station consists of DGPS receiver with antenna at a surveyed position, wind sensor, hand-held controller, and monitoring computer. And additional mission computer monitors the mission operations.

THE GPS/INS NAVIGATION LOOP

The GPS/INS navigation loop plays a key role in the UAV. The estimated vehicle states were used in the autonomous flight control module and other mission sensor nodes for target registration and picture compilation. It also has to provide precise timing synchronisation to other sensor nodes.

The strapdown INS is mechanized in an earth-fixed tangent frame as shown in Figure 3. In this mechanization scheme, the navigation frame is local-level or tangent to gravity and it is fixed on a ground reference point, which can be either the pilot position or the ground station.

Figure 2 Two flight vehicles (Brumby-MK3) (Left), FCC installed on fuselage with IMU, GPS, and tilt sensor (Upper Right), ISIS IMU (Lower Right), One of GPS antenna installed on the wing (Lower Right).

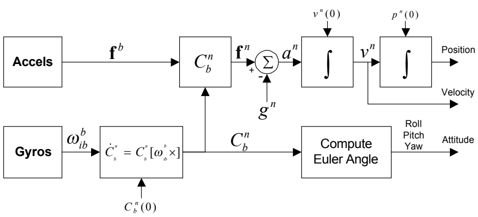

Figure 3 Strapdown INS mechanisation

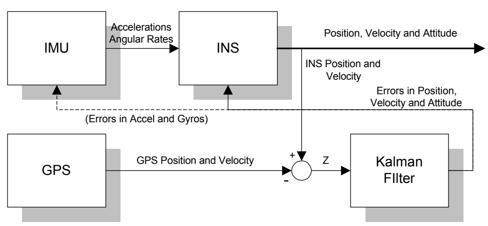

Figure 4 Indirect complementary fusion filters

As the ANSER mission profile has short flight duration and only cover several kilometres, the Coriolis effects due to rotation of earth and navigation frame are negligible. The change of gravity vector direction can also be ignored. The attitudes can be parameterised as Euler angles, quaternion, or direction cosine matrix (DCM). During flight, the direction cosine matrix parameter was used to update the attitude and they can be easily exchanged.

The INS initial alignment and calibration was performed using tilt sensors. The low-resolution gyros cannot detect the earth rotational rate, so the initial self-alignment technique for the heading cannot be used. More importantly, it introduces a rank deficiency in attitude estimation, which means from the observed velocity errors, three Euler angles are not fully observable [6]. To overcome this problem, additional external attitude aiding is required [6]. In this implementation, a two-antenna GPS system was configured to provide heading measurement to the filter. The MGA (Map Grid Australia) coordinate system is used as reference frame instead of WGS-84 coordinate system to exchange the vehicle states and relative target observations between UAVs.

The fusion filter is configured as an indirect complementary structure as shown in Figure 4. It makes use of 9 states of position, velocity, and Euler angle with INS error model as follow [7]

$$\begin{aligned} \delta \dot{r} &= \delta v \\ \delta \dot{v} &= a \times \psi + \nabla \\ \dot{\psi} &= \varepsilon \end{aligned} \tag{1}$$

Where, ψ is the misalignment angle, α is accel in NED frame, ∇ and ε are accel bias and gyro bias in NED frame respectively.

The GPS position and velocity are used to generate the observed INS position and velocity error. The indirect filter predicts the INS errors at 10Hz with this model and computes innovations with observed INS errors whenever GPS data is available. The innovation sequences are a good measure for filter consistency. If the INS errors are properly predicted from the filter then the innovation will represent only the GPS measurement noise, which is of a high frequency nature. In the actual implementation, the GPS receiver velocity shows a significant time delay compared to the position data, so velocity was not used in filter.

The hardware of the GPS/IMU navigation system is shown in Figure 3. with a low-grade IMU, two GPS receivers and two tilt sensors with a PC104 platform. The IMU is very light and small, which makes it suitable for UAV applications. Two CMC-Allstar^{TM} GPS receivers are stacked on the FCC and an antenna is installed on each of the wings as shown in Figure 3. The master GPS receiver provides navigation and raw measurement data to the filter and the slave receiver provides raw measurement data for attitude determination with carrier phase processing technique.
The GPS/IMU software was designed using the ANSI C++ class framework. The polymorphism and inheritance in C++ class methodology provides a great deal of modularity and efficiency in development. The developed software package was tested on different target platforms and on different operating systems. The main classes are divided into four groups; sensor interface class, attitude class, navigation class, and fusion filter class. The sensor interface class provides generic interface methods to various kinds of sensors, IMU, GPS receivers, and flight instruments. The attitude class contains various strapdown attitude update algorithms and can be parameterised using Euler class, quaternion class, and DCM class. Hence different attitude algorithms can be selected according to the specific application. The navigation class provides the strapdown navigation algorithm with various numerical integration schemes. The fusion filtering class implements a U/D factorised filter and standard covariance filter. The developed GPS/IMU navigation package was ported to embedded QNX real-time kernel in the FCC.

FLIGHT TEST RESULTS

A series of intensive flight tests were performed at Marulan, the test site of the University of Sydney. Each flight test had its own goals, which were characterisation of vehicle dynamics, tunning the GPS/IMU filter, payload operation, autonomous operation, and demonstration of ANSER goals with multiple UAVs. During each flight, all sensor nodes collected raw measurement data and were also tested for real-time operation. Typical vision data frame is shown in Figure 5 with two artificial targets on the ground. The vision computer identified these targets and registered them to the map using vehicle state information provided by the GPS/IMU navigation loop.
To evaluate the navigation performance a more precise navigation system that has an order of magnitude greater accuracy is required as a reference system. However due to the limited payload capacity of the UAV this could not be conducted. Instead, the standard deviation from the fusion filter was used to evaluate performance and the innovation sequence was used to check the filter consistency. The tilt sensors were also used to compare the attitude accuracy after landing.

A. Flight test on 17th of December 2001

A flight test was performed at Marulan on December 17, 2001. The main purpose of this test was to characterize the vehicle, to tune the GPS/IMU fusion filter, to collect vision data, and check the flight instruments. The total flight time was 13 min, the maximum flight height was 200m above ground and the maximum ground speed was 210km/h.
The visibility of GPS Satellite Vehicle (SV) was good. The number of SV observed was 11 at maximum and dropped to 7 during steep banking as shown in Figure 8. The maximum bank angle was 60 deg, which was required to meet the mission profile. Figure 9 shows the DGPS position accuracy reported from the receiver which showed 2m in horizontal and 3m in vertical on average. This information is fed into the fusion filter as a measurement uncertainty, which is more optimal than using the constant uncertainty value as the GPS accuracy varies according to the satellite geometry.
The estimated flight trajectory from the filter was quite smooth as shown in Figure 6. An enhanced view during taxing and take-off is shown in Figure 7. The estimated Euler angles are shown in Figure 10 with tilt sensor and GPS heading data for comparison. The tilt sensor is very accurate under static conditions, usually before and after flight, but it could not follow the high dynamics as can be seen from the plot of roll axis in Figure 10. Thus it was used only for calibration purposes.
The filter innovation with its 2σ uncertainties is shown in Figure 17 and it shows that most of the systematic INS errors are predicted out and is close to white sequence. The remaining systematic errors may come from un-modelled errors of INS, and GPS dynamics from its internal filter. It can be seen that the filter works properly and consistently from Figure 17.
The attitude errors can be estimated from the measured position error through the INS error model. Figure 18 shows the history of standard deviation of attitude errors from the filter. The roll and pitch error were maintained to 0.5 deg during the whole flight. However the heading error increased during static or cruising condition and decreased during dynamic conditions. This comes from the well-known observability issues of INS [8]. The standard deviation of the initial heading error was 10 deg and it dropped quickly as the vehicle began to move during take-off, the heading covariance increased during level flight and dropped during turns. One more interesting fact to note is during turning, although the uncertainty in the heading axis decreased, the uncertainties of roll and pitch axes increased. This comes from the fact that the low-quality GPS/IMU system does not have full rank even in maneuvering conditions [6].
The resulting navigation performance estimated from filter standard deviation is shown in Table 1.

Figure 5 Vision data with two targets.

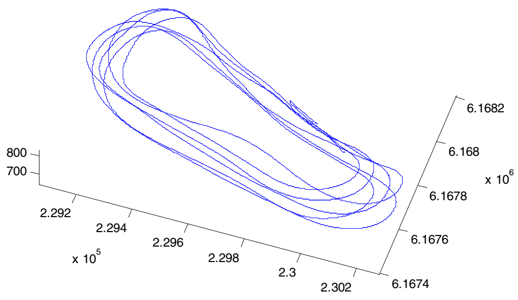

Figure 6 Flight trajectory from fusion filter.

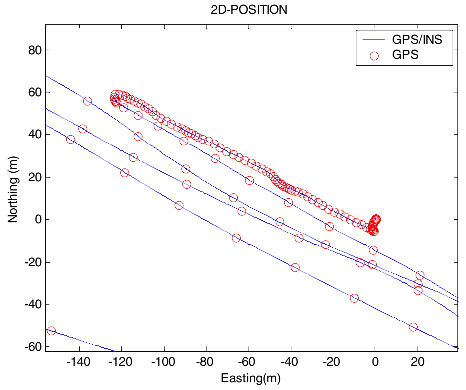

Figure 7 Enhanced view on take-off.

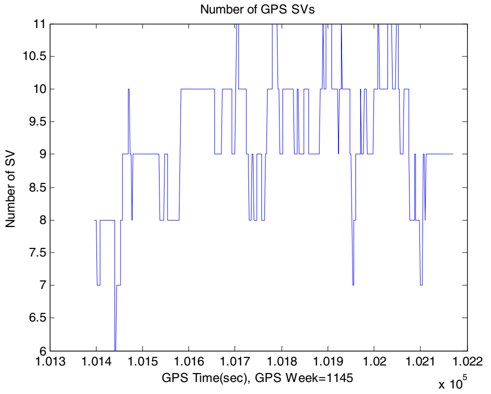

Figure 8 Visibility of GPS SV during flight.

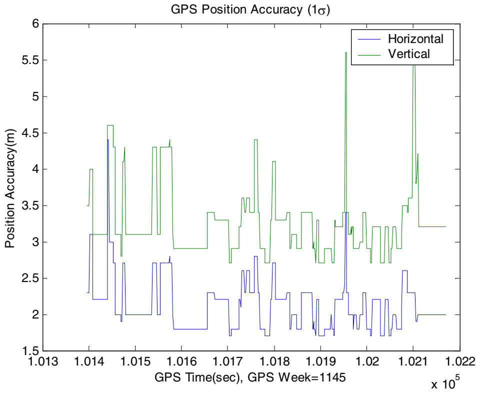

Figure 9 GPS position accuracy from receiver.

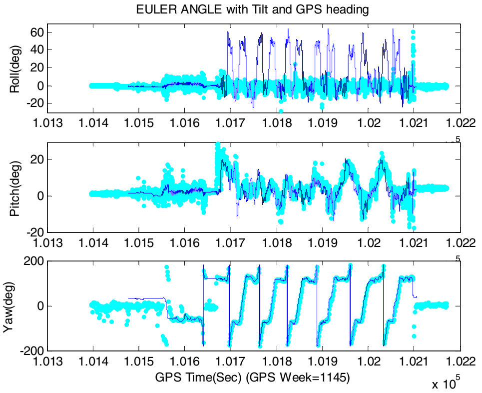

Figure 10 Attitude with tilt and GPS heading.

Table 1 Navigation performance measured from filter standard deviation (1σ) on 2nd July 2002

	N	E	D
Position (m)	2.0	2.0	3.0
Velocity (m/s)	0.2	0.2	0.3
Euler (deg)	0.3	0.3	0.8

B. Flight test on 2nd of July 2002

The purpose of this test was to demonstrate the ANSER DDF/PC between two flight platforms as shown in Figure 3. Two UAVs were equipped with two identical flight electronics, GPS/IMU filters, and vision payloads. One of the navigation results of UAVs is presented in this paper. The total flight time was 28 min and the maximum flight height was 160m above ground and maximum ground speed was 190km/h. The maximum

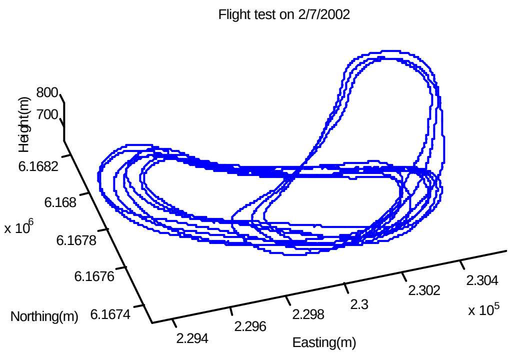

Figure 11 Estimated flight trajectory on 2/7/02.

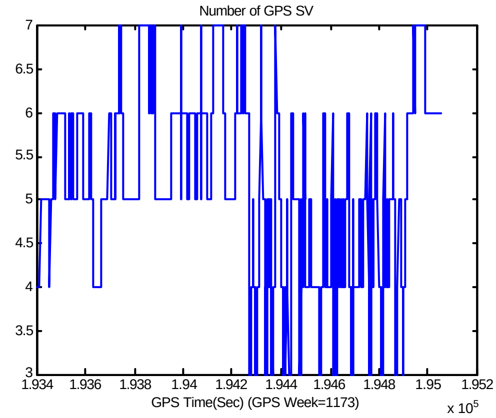

Figure 12 Visibility of GPS SV during flight.

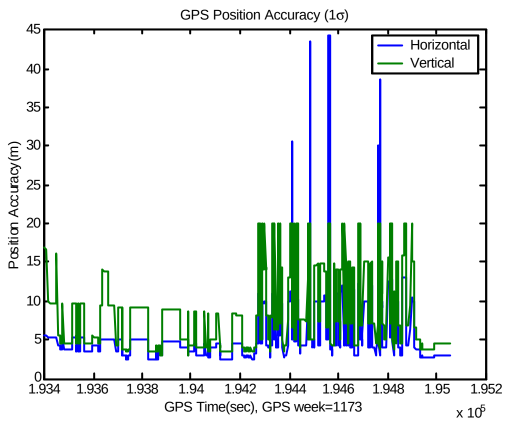

Figure 13 GPS position accuracy from receiver.

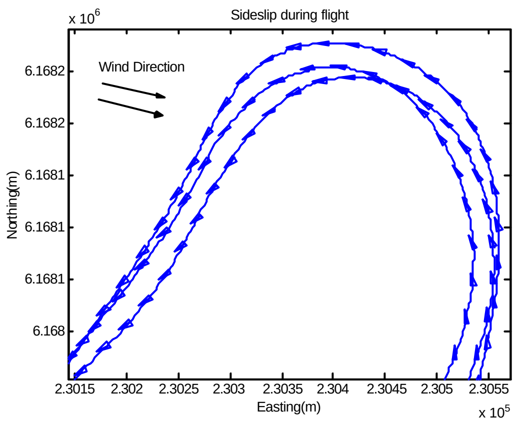

Figure 14 Side-slip during flight.

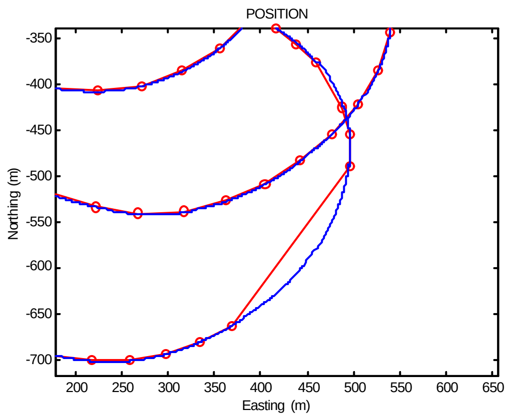

Figure 15 The loss of GPS data during banking

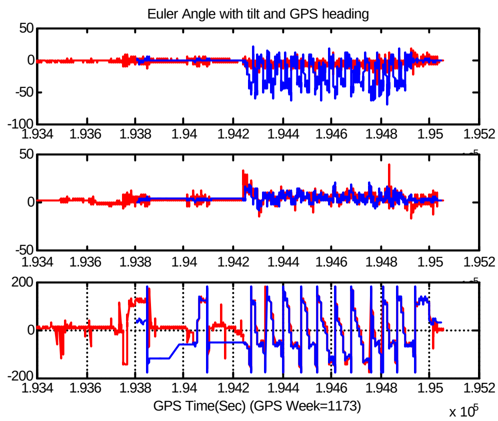

Figure 16 Attitude with tilt and GPS heading.

bank angle was 60deg. The estimated full flight trajectory from the fusion filter is shown in Figure 11. The visibility of GPS SV was poor on this day and the UAV could see only 6 SVs at maximum during level flight and it dropped frequently to 3 during steep turns. This caused the GPS receiver to enter the 2D height fixed mode as shown in Figure 12 and the reported GPS position accuracy varied from 3m to 10m in horizontal and from 4m to 20m in the vertical axis. Sometimes the UAV lost the DGPS link from the ground and GPS accuracy jumped up to 50m as in Figure 13. Although the GPS had poor quality, the GPS/IMU navigation loop provided robust and continuous solution as shown in Figure 15.

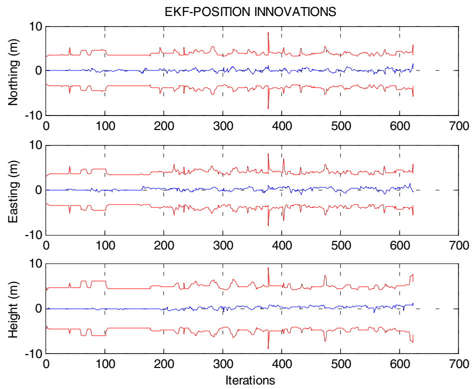

Figure 17 Position innovation (17/12/ 2002)

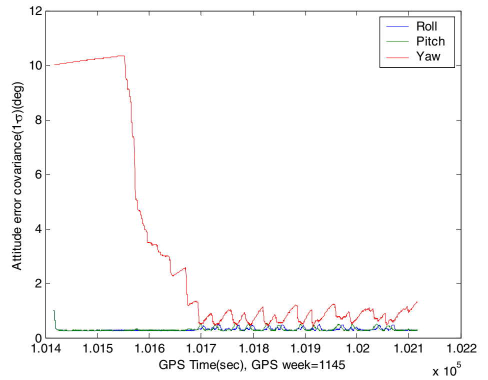

Figure 18 Standard deviations for attitude (17/12/ 2002)

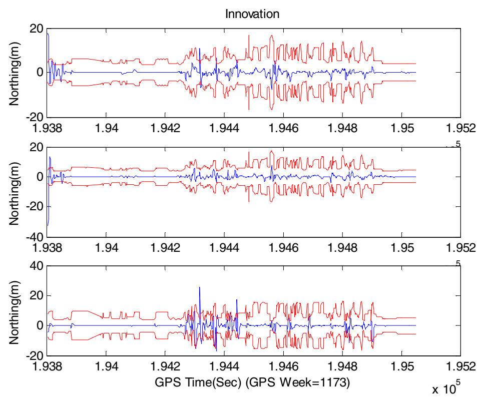

Figure 19 Position innovation (2/6/2002)

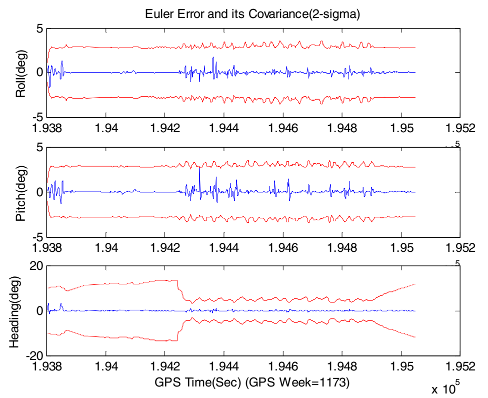

Figure 20 Standard deviations for attitude (2/6/2002)

A sideslip was observed during the whole flight due to the strong wind from the west as shown in Figure 14. The vehicle heading is clearly offset toward the wind direction from the ground velocity vector that is tangent to the flight trajectory. This can also be observed from the heading plot in Figure 16, where the GPS heading is calculated from the ground velocity vector.

The estimated Euler angles are shown in Figure 16 with tilt sensor and GPS heading data for comparison. Comparing them with tilt sensor outputs under static condition after landing, the accuracy of the attitude angles can be estimated. The attitude errors estimated from tilt sensors were 0.1 deg and 0.2 deg for roll and pitch, respectively.

Table 2 Navigation performance measured from filter standard deviation (1σ) on 2nd of July 2002.

	N	E	D
Position (m)	4.0	4.0	8.0
Velocity (m/s)	0.5	0.5	0.8
Attitude (deg)	0.5	0.5	1.0

Figure 19 presents the innovation sequence with its 2σ uncertainty. The uncertainty varied according to the change of GPS measurement uncertainty.

The resulting navigation performance estimated from filter standard deviation is shown in Table 2.

CONCLUSIONS

The GPS/IMU navigation loop was designed and tested for multiple UAV platforms. The fusion filter is designed as nine states, indirect complementary configuration. Two successful real-time flight tests showed 4m errors in horizontal and 8m errors in vertical although the number GPS satellites frequently dropped to 3 during maneuvering. The attitude errors were maintained under 0.5 deg in roll and pitch axis and 1.0 deg during flight test on 2nd of July 2002. Due to the lack of observability, the heading error will increase during level-flight and decrease on manoeuvring. In other words, to maintain the heading accuracy, frequent maneuvering is required during flight.

The GPS/IMU navigation loop worked properly to meet the mission demands, however, it is required to reduce the conning errors which occurred from the engine vibration to further increase the performance.

The internal GPS filter also introduced un-modelled dynamics and it caused the integration filter to be suboptimal. This made it difficult to tune the filter properly. The latter problem can be overcome by using tightly coupled integration structure with raw measurement GPS data.
Future work in GPS/IMU navigation loops will focus on incorporating a tightly coupled integration structure and using attitude GPS aiding from multi-antenna system.

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