Real-time Fault Detection Method for an AGPS/INS Integration System

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Abstract: The GPS/INS integration system navigation can provide improved navigation performance and has been widely used as a main navigation system for military and commercial vehicles. When two navigation systems are tightly coupled and the structure is complicated, a fault in either the GPS or the INS can lead to a disastrous failure of the whole integration system.

This paper proposes a real-time fault detection method for an AGPS/INS integration system. The proposed fault detection method comprises a BIT and a fault detection algorithm based on chi-square test. It is implemented by real-time software modules to apply the AGPS/INS integration system and van test is carried out to evaluate its performance.

Keywords: AGPS/INS Integration System, Fault Detection, Built-In-Test, Chi-square Test

1. INTRODUCTION

Inertial navigation system (INS) provides accurate navigation solution in short term and can have large low frequency errors that grow with time. Global positioning system (GPS), on the other hand, has high frequency noise with good long-term accuracy [1][2].

Since the INS and the GPS have complementary features, the GPS/INS integration system can overcome inherent drawbacks. Hence it has been widely used as a main navigation system for military and commercial uses. When the GPS/INS integration system is tightly coupled with two navigation system and its structure is complicated, a fault in either the GPS or the INS can lead to a disastrous failure of the whole system [2][3].

The fault of the integration system can be divided into two types; hard failure and soft failure [4]. The former is a failure which can influence the performance of system directly such as abrupt malfunction of the hardware. The latter does not affect the system immediately and can gradually degrade the performance of system with time. To achieve the real-time fault detection of integration system, many researches have been performed.

The built-in-test (BIT) technique has been investigated to detect the hard failure [5] and fault detection algorithms based on the mathematical model of system has been proposed for detection of the soft failure [6-8].

This paper proposes a real-time fault detection method for an AGPS/INS integration system. The proposed fault detection method comprises the BIT method and the fault detection algorithm based on chi-square test to sense the soft failures which cannot be detected by the BIT method. It is implemented by real-time software modules to apply the AGPS/INS integration system which consists of an AGPS receiver, a commercial inertial measurement unit (IMU), and a navigation computer unit (NCU) and van test is carried out to evaluate the performance of the proposed fault detection algorithm.

2. AGPS/INS INTEGRATION SYSTEM

Fig. 1 shows the overall structure of AGPS/INS integration system.

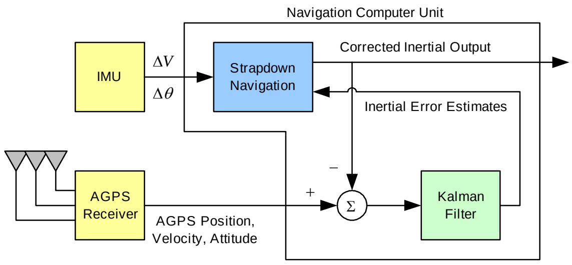

Fig. 1 AGPS/INS integration system

The AGPS/INS integration system divides into three parts; IMU, AGPS receiver, and NCU. The IMU gives velocity increment (ΔV) and angle increment ($\Delta \theta$). The AGPS receiver provides the attitude information as well as the position and the velocity information using multiple GPS antennas. The NCU performs the strapdown navigation and the Kalman filter algorithm. The strapdown navigation computes the position, the velocity, and the attitude from the inertial measurements. The details in its algorithm are described in well-known literatures [9-11]. The Kalman filter estimates the inertial errors from the strapdown navigation result and the outputs of the AGPS receiver. The error model of the Kalman filter contains 15 error state; 3 position error, 3 velocity error, 3 attitude error, 3 gyro bias, and 3 accelerometer bias [12].

3. REAL-TIME FAULT DETECTION METHOD

3.1 Hard failure detection using BIT method

The hard failure detection is consists of the hardware test of NCU, IMU and AGPS receiver. The hardware test of NCU is carried out by three phase; EEPROM (Electrically Erasable Programmable Read Only Memory) test, RAM (Random Access Memory) test, and external I/O (Input/Output) interface test. Fig. 2 shows the procedure of EEPROM test. The 4 byte EEPROM ID is pre-stored in the specific address in EEPROM which contains the software of integration system. When the CPU is initialized at power-on, the pre-stored EEPROM ID is read and compared with the predetermined value in the EEPROM test routine. If the EEPROM ID is not consistent with the predetermined value, the EEPROM test routine decides that the EEPROM has a fault.

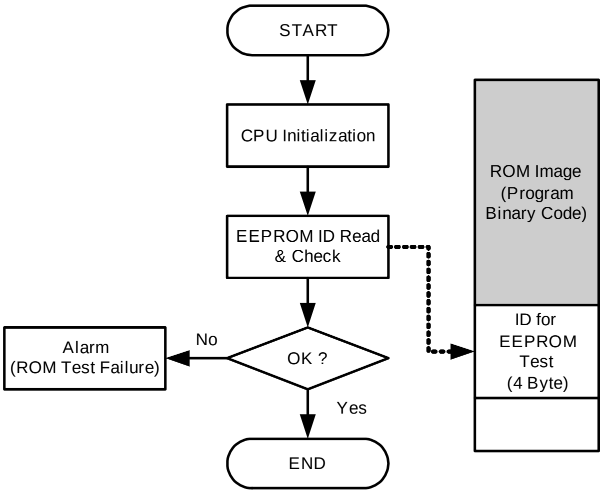

Fig. 2 Procedure of ROM test

Fig. 3 shows the procedure of RAM test. The RAM test is performed by writing and reading the test pattern from base address to end address of the RAM. If the written test pattern is not consistent with the read value, the RAM test routine decides that the RAM has a fault.

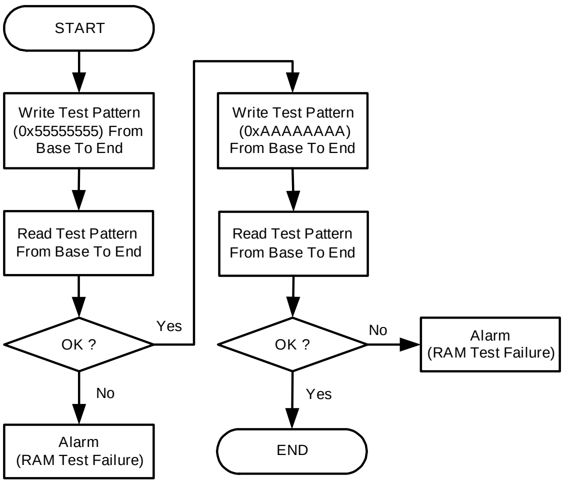

Fig. 3 Procedure of RAM test

Fig. 3 shows the procedure of external I/O interface test. The external I/O interface test is performed by using the loopback test function embedded in the I/O device at the initialization of each device. When the NCU test is completed, the IMU and AGPS test is started. The IMU test is executed by checking the status word of IMU data message frame which indicates the self test results. Also, the AGPS receiver test is performed by checking the self test result to confirm whether or not that the operation of AGPS receiver is normal.

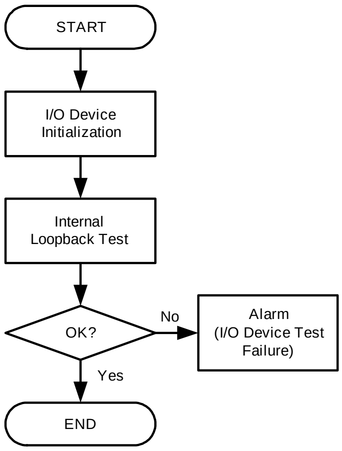

Fig. 4 Procedure of I/O device test

3.2 Soft failure detection

In normal condition, the residual of integration Kalman filter is white Gaussian sequence. The statistical characteristic of the residual will be changed when a GPS or an INS fault occurs. The proposed algorithm detects the faults of integration system by checking the consistency of statistical characteristic of residual vector [6-8].

The model for the system state $\mathbf{x}_k$ and the measurement $\mathbf{z}_k$ at time t_k are

$$\mathbf{x}_{k+1} = \boldsymbol{\phi}_k \mathbf{x}_k + \mathbf{w}_k, \quad \mathbf{w}_k \sim N(0, \mathbf{Q}_k) \tag{1}$$

$$\mathbf{z}_k = \mathbf{H}_k \mathbf{x}_k + \mathbf{v}_k, \quad \mathbf{v}_k \sim N(0, \mathbf{R}_k) \tag{2}$$

where $\boldsymbol{\phi}_k$ and $\mathbf{H}_k$ are state transition matrix and measurement matrix at time t_k, respectively; $\mathbf{w}_k$ and $\mathbf{v}_k$ are independent, zero mean, Gaussian white sequence at time t_k having covariance of $\mathbf{Q}_k$ and $\mathbf{R}_k$ at time t_k, respectively.

The residual vector $\boldsymbol{\gamma}_k$ at time t_k is zero mean, Gaussian white sequence at time t_k having covariance of $\mathbf{V}_k$.

$$\boldsymbol{\gamma}_k = \mathbf{z}_k - \mathbf{H}_k \mathbf{x}_x, \quad \boldsymbol{\gamma}_k \sim N(0, \mathbf{V}_k) \tag{3}$$

The $\mathbf{V}_k$ is

$$\mathbf{V}_k = \mathbf{H}_k \mathbf{P}_k \mathbf{H}_k^T + \mathbf{R}_k \tag{4}$$

where $\mathbf{P}_k$ is an error covariance matrix.

A test for the occurrence of a failure is comparing the scalar test statistic

$$l_k = \sum_{i=k-N+1}^{k} \boldsymbol{\gamma}_i^T \mathbf{V}_i^{-1} \boldsymbol{\gamma}_i^T \sim \chi_{Np}^2 \tag{5}$$

with a constant threshold. The symbol N and p denotes the window size and the dimension of the residual vector, respectively. The test statistic l_k is chi-square distributed with $N \cdot p$ degrees of freedom.

The test for the fault detection is

$$\begin{array}{ll} l_k \geq \varepsilon & \text{fault} \\ l_k < \varepsilon & \text{no fault} \end{array} \tag{6}$$

where the decision threshold ε is determined from the window size N and the false alarm rate with the table of the chi-square distribution.

4. TEST RESULTS

4.1 Experimental setup

Fig. 5 shows the experimental setup in the test van. The AGPS receiver provides C/A code tracking on 36-channels at the L1 frequency simultaneously. It offers the position, velocity, attitude, raw measurement data and GPS time at 1 Hz [13]. The HG1700AE IMU manufactured by Honeywell Inc. provides inertial measurements at 100 Hz. Table 1 shows the error characteristic of IMU. The NCU performs the integration algorithm and provides the computed navigation results to the FCC. It equipped multiple serial interfaces to operate with various sensors.

Table 1. Error characteristic of IMU

Item	Error (1σ)
Gyro Bias	1.0 deg/hr
Gyro Noise	80 μrad
Aceel. Bias	1 mg
Aceel. Noise	0.008 ft/s

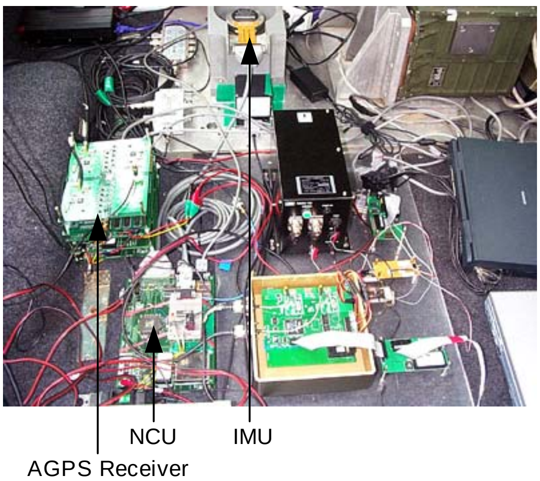

Fig. 5 Experimental setup in test van

4.2 Experimental result

Before the start of van test, the BIT is performed to detect the fault of integration system hardware. The BIT results confirm that there are no hardware failures in the integration system. To evaluate the effectiveness of fault detection algorithm for soft failure detection during the integrated navigation, the test van was carried out by driving on the rectangular test path for 947 seconds. The number of the tracked satellites is presented in Fig. 6.

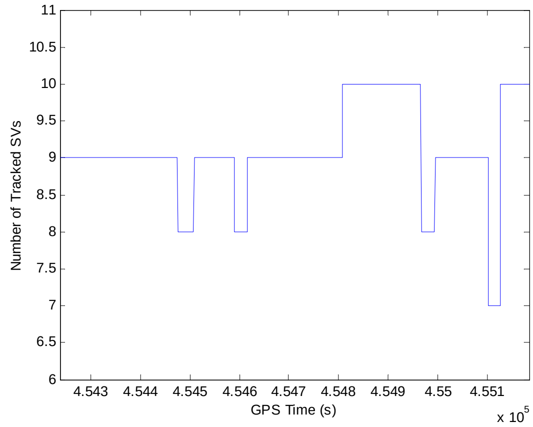

Fig. 6 Number of Tracked Satellites

Fig. 7 shows the horizontal position result without fault detection algorithm. In Fig. 6, the reduction of the number of the tracked satellites caused the abrupt jumps in the GPS position data. If the fault detection algorithm was not applied to the integration system, its navigation results closely followed the erroneous GPS data.

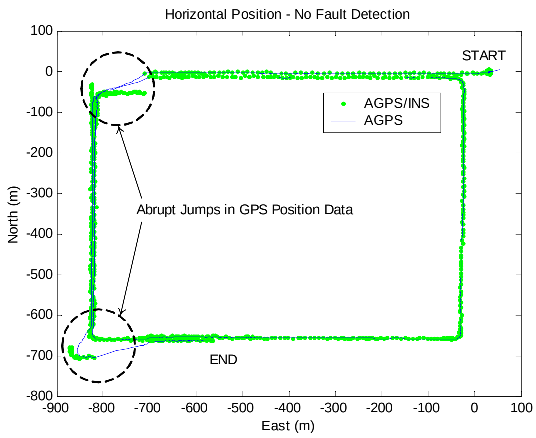

Fig. 7 Horizontal position result without fault detection

Fig. 8 shows the fault detection result. The window size of fault detection algorithm was selected as 5 and the false alarm rate as 0.5%. From the window size and false alarm rate, the decision threshold was determined as 32.8 using the table of chi-square distribution. If the test statistic exceeded the threshold, the fault detection algorithm decided that the fault occurred in the integration system. The fault detection results were exactly consistent with the abrupt jumps in the GPS data.

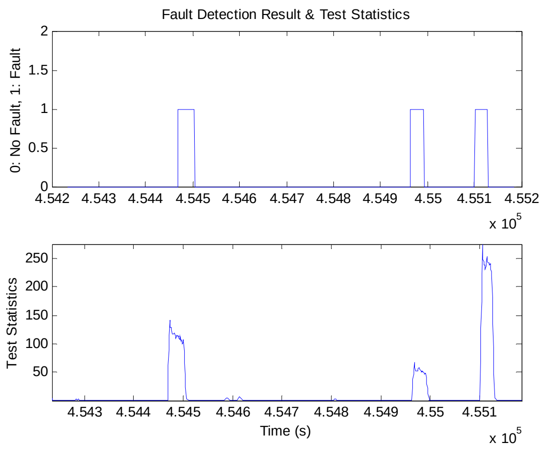

Fig. 8 Fault detection result and test statistic

Fig. 9 shows the position result with the fault detection algorithm. The experimental result showed that the integration system could provide accurate navigation result by using the fault detection algorithm, even when abrupt jumps were in the GPS data.

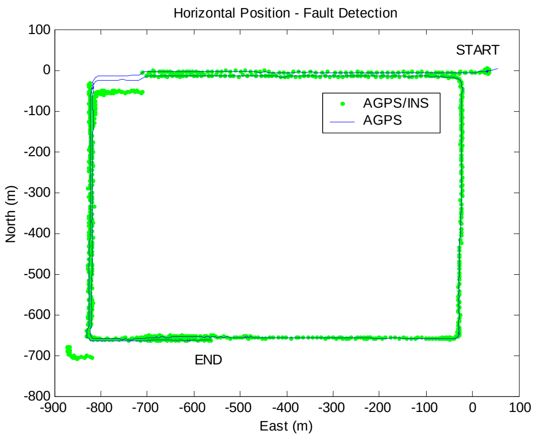

Fig. 9 Horizontal position result with fault detection

5. CONCLUSION

In this paper, a real-time fault detection method for an AGPS/INS integration system is proposed. The proposed fault detection method comprises the BIT and fault detection algorithm based on chi-square test to detect both the hard and the soft failure. Van test was carried out to assess the performance of proposed fault detection method. The integration system provides accurate navigation result even when abrupt jumps occur in GPS position data.

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