# Attitude Heading Reference System Based Vehicle Stationary State Detection

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***Abstract*—Vehicle navigation is a crucial requirement for many applications. Global Positioning System (GPS) can provide accurate navigation information. But the GPS performance degrades and even a complete outage may occur in urban areas due to line of sight problem. Inertial Navigation System (INS) can provide navigation information during a GPS outage. However, due to bias, drift, noise and other errors, the position information quickly diverges which is more sever for low cost INS. These errors can be corrected in a stationary state. Detecting the stationary state to correct the INS error is crucial for navigation system. This paper proposes a novel stationary detection technique by the threshold approach with an Attitude Heading Reference System (AHRS) built from the Inertial Measurement Unit (IMU) sensors and acceleration information. The stationary state is detected from variance of the acceleration data and the heading of the vehicle. The test result shows that the 87% correct stationary state is detected from both the acceleration and heading information. The stationary state detection can help to correct the INS errors.**

***Keywords—AHRS; GPS; INS; navigatyion; ZUPT***

## I. Introduction

Navigation has been used since ancient days. It is comprised of the methods and technologies to determine the time varied position, velocity and attitude of a moving body [1-2]. Global Positioning System (GPS) and Inertial Navigation System (INS) are popular navigation devices of the modern days [3]. GPS can provide excellent navigation with low update rate where the satellite signals are not obstructed [4]. However, the performance severely diminishes or even complete outage occurs in tunnels, urban areas with skyscrapers or in underground parking garages [5]. On the other hand, the INS can provide continuous navigation information with high data rate which does not depend on any external sources like the satellites of the GPS. But the downside is that the accuracy of the INS largely depends on the quality of the IMU.

IMU generally consists of three orthogonal accelerometers and gyroscopes. Besides, the magnetometer is also widely used nowadays. Theoretically, single and double integration of the acceleration from accelerometer provides velocity and position information. But in reality the non-linearity, bias, drift and the noise of the sensors make accuracy of the predicted trajectory valid for short time [6]. The recent advances in Micro Electro Mechanical Systems (MEMS) led to very inexpensive IMU sensors [3, 7]. But the bias, drift, noise characteristics and the overall accuracy are of inferior [8]. The gyroscope of a low cost IMU cannot sense the rotation of the earth like the he gyroscope of a tactical grade INS [9]. Moreover, the acceleration sensed from the accelerometer of the low cost IMU are very noisy besides the bias error [10]. Due to the drift, bias and other noises, the position derived from the double integration of the acceleration sensed from the accelerometer and the orientation derived from the accelerometer and gyroscope gives rise to an error in position which increases as the cube of time [10].

The performance of a low cost MEMS based INS can be improved significantly. The biases and the drifts of the sensors can be improved by integrating with an aiding measurement like GPS [11]. However, the performance of the GPS degrades or even a complete outage can occur due to the line of sight problem which in turn affects the navigation performance of the low cost INS. This inspires for alternative techniques to reduce the bias and drift errors of the low cost INS. Several researchers suggested the stationary update as an alternative technique which is popularly known as Zero Velocity Update (ZUPT) [11]. The ZUPT utilizes the zero velocity condition or the stationary state to estimate the systematic errors of the IMU sensors as well as the attitude errors [12]. When the unit is stationary, the only forces acting on the unit are the gravitational force and the rotation of the earth. Beyond these forces, others should be errors in the form of bias, noise or drift which can assist the popular estimation filters like Kalman filter in getting the differences between the static model and the actual observation to estimate the errors. In urban areas, these stationary states occur frequently due to the traffic congestion and intersection traffic signal. Thus, the correction can be performed at regular interval and the estimation error of the low cost INS can be kept minimum during a GPS outage [12].

Several researchers worked on various methods for detecting the ZUPT or the stationary state. The majority of the works were focused on pedestrian and indoor navigation where the sensor errors are corrected when the foot of the pedestrian touches the ground. These approaches are not applicable to land vehicle system [11]. This paper proposes a novel stationary detection technique for a vehicle to correct the IMU sensor errors by the threshold approach of an Attitude Heading Reference System (AHRS) built from the IMU sensors.

## II. SENSOR MODEL AND ATTITUDE HEADING REFERENCE SYSTEM

Present day, MEMS based IMUs are equipped with triaxial accelerometers and gyroscopes, at times accompanied with magnetometers. These sensors are aligned with the body (b) frame where x-axis is along the forward movement direction of the vehicle, y-axis is towards to right side of the vehicle and z-axis follow the orthogonal right handed rule [7]. Body frame axes are also aligned with roll, pitch and yaw axes. A generalized inertial sensor model is given in (1) [11].

$$\tilde{y}_b = y_b + b_b + n \tag{1}$$

where $y_b^T = [f_b^T \quad \omega_{ib}^{b\,T}]$ and $f_b = a_b + {}_n^bRg_n$ is the specific force vector. The vector $y_b$ is corrupted by measurement noise $n$ and slowly varying bias $b_b^T = [{}^ab_b^T \quad {}^gb_b^T]$ where ${}^ab_b$ and ${}^gb_b$ are the accelerometer and gyroscope biases. $a_b$ denotes the acceleration in body frame and $g_n$ is the gravity vector in navigation frame expressed as $g_n^T = 0 \quad 0 \quad g_e$ where $g_e \approx -9.8m/s^2$ . All the biases are modeled as random walk.

The INS error state vector can be expressed by (2).

$$\delta x^T = [{}^b\delta p_n^T \quad {}^b\delta v_n^T \quad \rho_n^T \quad {}^a\delta b_b^T \quad {}^g\delta b_b^T] \tag{2}$$

where ${}^b\delta p_n$ denotes the position error and ${}^b\delta v_n$ denotes the velocity error in navigation frame. ${}^a\delta b_b$ and ${}^g\delta b_b$ denotes the accelerometer and gyroscope bias in body frame, respectively. $\rho_n^T$ denotes the small rotation angle transformed from estimated to actual navigation frame.

By utilizing the IMU sensors, an AHRS can be constructed which can provide the orientation of a vehicle in terms of roll, pitch and yaw information. The integrated output of the gyroscope combined with accelerometer output can pin down the drift of the gyroscope and can provide roll and pitch information. But the accelerometer cannot provide any yaw information. The integrated output provided by the gyroscope cannot alone be trusted as the low cost gyroscope drifts quickly. The magnetometer can aid to get the better yaw or heading information with its reading in relation to Earth's magnetic field. Thus, a fusion algorithm is required to determine the roll, pitch and yaw information.

The fusion algorithm utilizes the complementary filter where the gyroscope derived attitude is passed through a high-pass filter and the accelerometer derived attitude is passed through the low pass filter. The block diagram of the fusion algorithm is shown in Fig. 1. The fusion of the roll angles from gyroscope and accelerometer is done in a complementary filter. Another complementary filter is used for the fusion of pitch angles derived from the gyroscope and accelerometer. The heading derived from the gyroscope is corrected with the heading derived from the magnetometer and the fusion is done by another complementary filter.

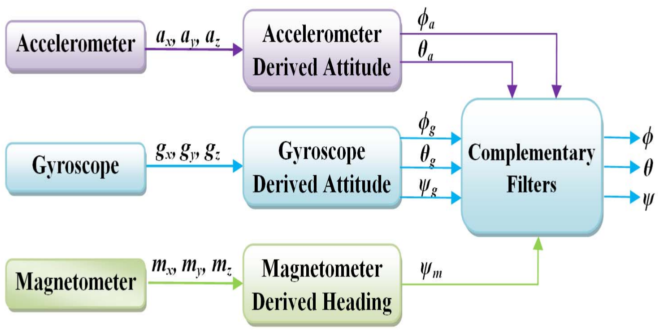


Fig. 1. Block diagram of the fusion algorithm for AHRS.

## III. ZUPT THEORY

The stationary condition of a vehicle allows improving the navigational performance of a low cost IMU. When the vehicle is in rest position, the only forces acting on is gravity of the earth and the force from the earth rotation [13]. So, when the vehicle is in stationary position, the velocity ( $v_b$ ) and angular rate ( $\omega_b$ ) should be zero. The difference between the static and actual observation can be used in the Kalman filter to estimate the errors. With the imposed zero measurement velocity, the measurement and the linearized model of the velocity residuals are calculated by (3) and (4), respectively. The measurement and the linearized model of the angular rate residuals for the gyroscope are calculated by (5) and (6), respectively.

$$\delta v_b^n = \tilde{v}_b^n - \hat{v}_b^n = -\hat{v}_b^n \tag{3}$$

$$\delta v_b^n = H_v \delta x \tag{4}$$

$$\delta \omega_b^n = \tilde{\omega}_b^n - \hat{\omega}_b^n = -\hat{b}_b^n \tag{5}$$

$$\delta \omega_b^n = H_\omega \delta x \tag{6}$$

## IV. DETECTION OF THE STATIONARY STATE

No stationary sensors are available [11]. An odometer can be used to detect a stop condition. But, the odometer needs an additional installation and also not available in all vehicle. Thus, the stationary updates are pseudomeasurements. The IMU reading for vehicle in motion or at constant cruise will have inconsistent reading due to road condition and engine vibration. This can be utilized to detect a stationary condition. The static detection algorithm needs to be designed keeping the easy implementation, simplicity, practicality and robustness in consideration. A reliable stop detection algorithm can be one that is based on the analysis of the variance of an accelerometer, gyroscope and magnetometer signal. The accelerometer output during the movement of a vehicle varies significantly due to the engine vibration, road condition, wind etc compared with the stationary states. In a stationary state, the accelerometer output includes only gravity, bias and noise accompanied with the environmental disturbances. The heading from the gyroscope output also varies significantly while the vehicle in moving condition compared with a stationary condition [14]. Similarly, the magnetic heading from the magnetometer also varies in moving condition compared with the stationary condition. Thus, the acceleration and the heading are considered for the stationary detection.

The acceleration from the accelerometer in sensor frame at time $t_k$ for three axis ($a_x, a_y, a_z$) are transformed to an acceleration vector $\vec{a}_k$. During a complete stop, the variance of $\vec{a}_k$ is checked against a threshold. The threshold is determined through a short initial learning phase. The mean $\mu_a$ and variance $\sigma^2{}_a$ of $\vec{a}_k$ are computed. The stationary condition is detected within a time window which is calculated using (7). The decision on stationary is made on computed deviation of $\sigma_a$ and variance of $\|\vec{a}_k\|$. Similarly, the stop condition is detected through the deviation and variance of heading from the AHRS.

$$\sigma_a = \sqrt{\frac{1}{N}\sum_{k=1}^{N}(\|\vec{a}_k\| - \mu_a)^2} \tag{7}$$

where $N$ is the number of samples inside the time window

## V. Experimental Results

The 9DoF Razor IMU from Sparkfun Electronics was used in the experiment. It incorporates a triple-axis gyro (ITG-3200), a triple-axis accelerometer (ADXL345) and a triple-axis magnetometer (HMC5883L) in a single board. The outputs of all sensors are processed by the on-board ATmega328 microprocessor with 13-bit resolution over a serial interface at a maximum 57,600bps. A 42 channel GPS receiver powered with high performance STE engine was used in the experiment. With -160dBm tracking sensitivity and <2.5m CEP, it offers good navigation performance in urban areas and limited sky view with 1Hz update rate. For the fusion, the Arduino Mega 2560 microcontroller board based on the ATmega2560 was used. It has 54 digital input/output pins, 16 analog inputs, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button. With 256KB of memory and 16MHz clock speed, the board is suitable for the experiment. The IMU module was connected to the serial port of the board.

The Razor IMU was rigidly fixed inside in the test vehicle. The GPS was installed on the dashboard for a better line of sight. The IMU was set to capture data at 50Hz. With the complete module, the test vehicle was driven in Jalan Reko, Kajang of Malaysia in the first test and Persiaran Bangi, Malaysia in the second test. There were two traffic signals where the vehicle stopped in the first test. The acceleration of the vehicle is shown in Fig. 2. Around 2800 sample time, the vehicle stopped in the first traffic signal. The variance and deviation correctly detected the stationary condition from the acceleration signal. Similarly, the vehicle again stopped in the second traffic signal around 4850 sample time and the stationary state was detected.

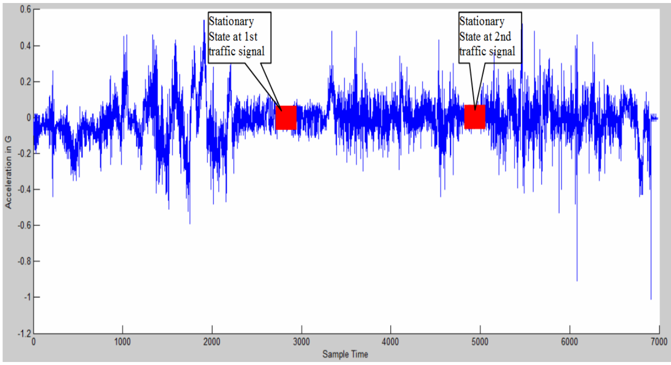


Fig. 2. Stationary detection from acceleration signal in the first test.

There were four traffic signals where the vehicle stopped. The acceleration of the vehicle is shown in Fig. 3. Around 1800 sample time, the vehicle stopped in the first traffic signal. The variance and deviation correctly detected the stationary condition from the acceleration signal. Next the vehicle stopped in 4300 sample time and 6800 sample time and the stop situations were correctly detected. Again the vehicle stopped in 8700 sample time in the fourth traffic signal which was also correctly detected. In 9800 sample time, the vehicle did not stop but the false stop was detected.

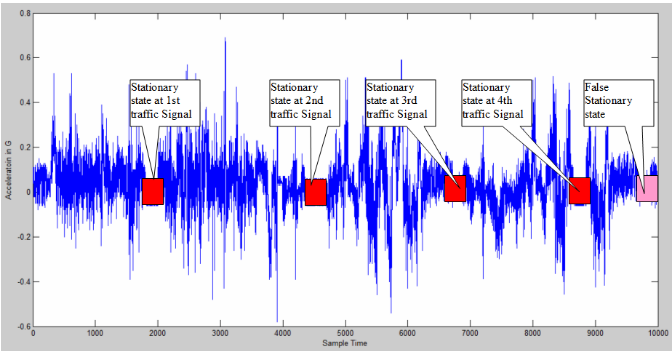


Fig. 3. Stationary detection from acceleration signal in the second test.

From the AHRS data, the heading of the vehicle was analyzed. The heading of the vehicle is shown in Fig. 4 for the first test and in Fig. 5 for the second test. In the first test, around 2800 sample time, the vehicle stopped in the first traffic signal. The heading of the vehicle unchanged within the predetermined time window. Thus, it was detected as a stationary condition. Similarly, the vehicle stopped in at 4850 sample time. At this time also, the heading remain unchanged. Thus, the stationary state of the vehicle was detected.

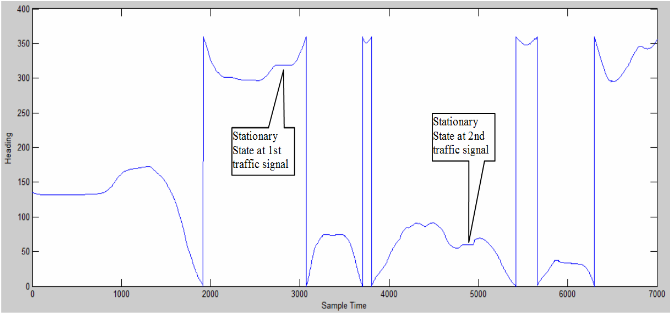


Fig. 4. Stationary detection from heading in first test.

In the second test, around 1800 sample time, the heading of the vehicle did not change and thus it was detected as a stationary condition. Again, at 4300 sample time, the heading did not change which coincided with the accelerometer stationary detection condition. Thereby, it was detected as a stationary state. The similar detection occurred at 6800 sample time and 8700 sample time. In 9800 sample time, the heading was unchanged and it was identified as stationary condition. But the vehicle only slowed down and did not stop during that time. Thus, it was not correctly identified as a stationary condition.

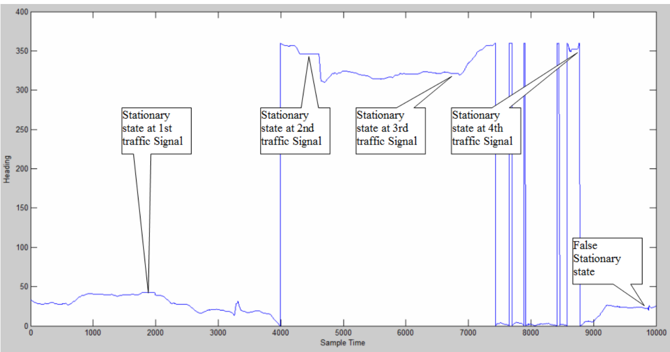


Fig. 5. Stationary detection from heading in second test.

The proposed method utilized both the acceleration and heading data from the IMU to detect the stationary state. Combining these two data, the false alarm rate was reduced. The result of the first and second tests were evaluated to determine the false alarm rate using (8). There were total seven stops detected. Out of these seven, one was not correctly detected. So, the correct detection rate is 86% and the false detection rate is 14%.

$$CorrectDetection = \frac{ActualStopDetected}{TotalStopDetected} \times 100 \tag{8}$$

## VI. Conclusion

Stationary state detection is crucial to correct the INS errors. With the threshold technique applied to the acceleration and heading information, the stationary detection method is proposed in this paper. Combining both the acceleration and heading data, the proposed method reduced the false alarm rate of stationary detection as the false stationary detection is disastrous. The proposed method would help to reduce to INS error and enhance the performance of the navigation system in GPS outage condition.

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