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ORIENTATION OF AIRCRAFT USING EXTENDED KALMAN FILTER

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ABSTRACT

This work describes the designing of AHR System with TGIC (Two Step Geometrical Intuitive Correction) algorithm using Kalman Filter to provide a proper orientation. A multi sensor IMU is required because a single type sensor cannot provide accurate attitude estimation. The acce1erometer is sensitive to vibrations. A gyroscope is susceptible to low-frequency drift and wideband measurement noise, resulting in accumulation of bias, and the magnetometer readings get distorted due to the ferrous materials (magnetic material). Therefore, it is passed through a correction algorithm to reduce these distortions. TGIC with Kalman Filter helps in reducing these distortions. AHRS application includes Drones (UAVs), navigation tracking etc. Kalman filter is an estimation algorithm. It's a method of calculating the future state of a system based on the prior state. We are using a quaternion based Extended Kalman filter, where the quaternion with the gyro bias represents the state vector. Including the bias that is in the state vector gives ability to track the bias and model the drift in Kalman filter to reduce error.

KEYWORDS: *Attitude, Extended Kalman Filter, TGIC, Navigation Tracking*

Article History

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INTRODUCTION

An attitude and heading reference system (AHRS) is made up of sensors on three vertices that give attitude info for the aircraft, i.e. roll, pitch and yaw. These are referred to as MARG (Magnetic, Angular Rate, and Gravity) sensors and are of either solid or micro electro mechanical system known as (MEMS) consisting gyroscopes, accelerometers and magnetometers. They are designed to replace traditional mechanical gyroscopic flight instruments.

[1] A type of non-linear estimation system such as Ex-tended Kalman filter is usually used to compute the result from these sources. AHRS have been proven to be highly dependable and are in common use in all types of aircrafts. AHRS are typically paired with electronic flight instrument systems (EFIS) to form the primary flight display. AHRS are combined with air data computers to create an “air data, attitude and heading reference system” (ADAHRS), which provides information like air-speed, altitude and air temperature. With sensor fusion, drift from gyroscopes integration is made up for by the reference vectors, gravity, and the earth’s magnetic field. This results in a drift-less orientation, making an AHRS a

more cost operative solution than traditional IMUs (Inertial Measurement Units) that only integrate gyroscopes and work on a high bias stability of the gyroscopes.

AHRS Model

Figure 1 Air traffic control - standard international practice is to monitor airspace using two radar systems: primary and secondary.

Primary radar -based on the earliest form of radar developed in the 1930s, detects and measures the approximate position of aircraft using reflected radio signals.

Secondary radar - which relies on targets being equipped with a transponder, also requests additional information from the aircraft - such as its identity and altitude.

All commercial aircraft are equipped with transponders (an abbreviation of "transmitter responder"), which automatically transmit a unique four-digit code when they receive a radio signal sent by radar.

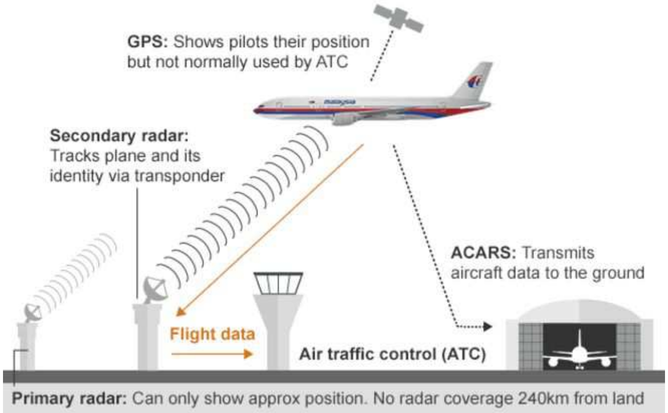

Figure 1: Radar Based Flight Tracking System.

The code gives the plane's identity and radar stations go on to establish speed and direction by monitoring successive transmissions. This flight data is then relayed to air traffic controllers. However, once an aircraft is more than 240km (150 miles) out to sea, radar coverage fades and air crew keep in touch with air traffic control and other aircraft using high-frequency radio.

To reduce the computational time, and improve the pitch/roll approximation accuracy of the low-cost attitude heading reference system in conditions of magnetic-distortions, an innovative linear Kalman filter, apt for nonlinear attitude estimation, is projected in this paper. The novel algorithm is the amalgamation of two-step geometrically-intuitive correction and the Kalman filter[2].

Two-step system is used to make the present approximation of pitch/roll resistant to magnetic distortions. The TGIC outputs a calculated quaternion for the Kalman filter, which evades the linearization error of measurement equations and decreases the computational time.

Figure 2 is the block diagram of proposed AHRS system; Figure3 shows orientation across axes. As Accelerometer is sensitive to vibrations. ADXL345 is a 3-axis accelerometer with high resolution (13-bit) measurement at up to ±16 g, its value are passed through a low-pass filter. Mag (m) values from magnetometer HMC5883L a surface-mount, multi-chip module designed for low-field magnetic sensing with a digital interface and the BMP-085 is digital pressure sensor which has high accuracy and long term stability. And low passed accelerometer values are then given to TGIC to correct the estimated direction of gravity and convert to the quaternions (q). These quaternions and gyro values from gyroscope L3G400D a low-power three-axis angular rate sensor are then passed through the Kalman filter. Kalman filter keeps the track of the bias and helps in removing the error through prediction and updation step which gives the corrected value of roll (ϒ), pitch(Θ) and yaw(ψ).

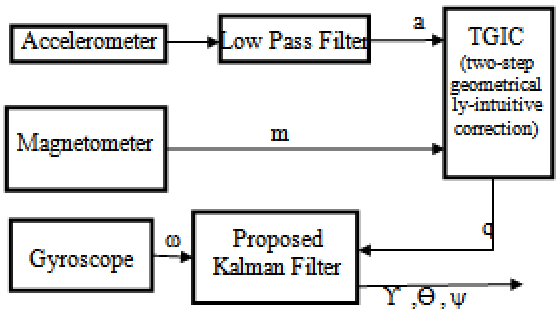

Figure 2: Block Diagram of Proposed AHRS System.

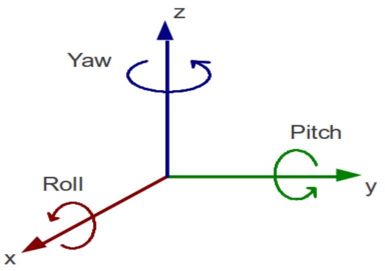

Figure 3: Orientation across the Axes.

To detail the orientation, set the body frame a xyz, the navigation frame m North, Down, East (NDE). The y-axis is oriented towards the forward, the x-axis is oriented towards the down and the z-axis is oriented towards the right [2]. The angle of the body could be gotten from an attitude transformation matrixC_m^a. C_m^a is a perpendicular matrix and can be summed through 3 separate rotations around the 3 axes. The first rotation is along the y-axis by, the second revolution is around the z-axis by, and the third spin is around the x-axis by; they are given as:

$$C_\psi^y = \begin{bmatrix} \cos\psi & 0 & \sin\psi \\ 0 & 1 & 0 \\ -\sin\psi & 0 & \cos\psi \end{bmatrix}, C_\theta^z = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}, C_\gamma^x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\gamma & -\sin\gamma \\ 0 & \sin\gamma & \cos\gamma \end{bmatrix} \tag{1}$$

$$C_n^b = C_\gamma^x C_\theta^z C_\psi^y = \begin{bmatrix} \cos\theta\cos\psi & \sin\theta & -\sin\psi\cos\theta \\ -\cos\gamma\cos\psi\sin\theta + \sin\gamma\sin\psi & \cos\gamma\cos\theta & \sin\psi\sin\theta\cos\gamma + \cos\psi\sin\gamma \\ \sin\theta\sin\gamma\cos\psi + \cos\gamma\sin\psi & -\sin\gamma\cos\theta & -\sin\theta\sin\gamma\sin\psi + \cos\psi\cos\gamma \end{bmatrix} \tag{2}$$

Because of the disadvantages of the Euler angle, quaternion a_p^m = [p0 p1 p2 p3] is utilized to mean the attitude of the m frame in reference to a frame. Therefore, the direction cosine matrix (DCM) can be represented in quaternion:

$$C_n^b = \begin{bmatrix} q0^2 + q1^2 - q2^2 - q3^2 & 2q0q3 + 2q1q2 & -2q0q2 + 2q1q3 \\ -2q0q3 + 2q1q2 & q0^2 - q1^2 + q2^2 - q3^2 & 2q0q1 + 2q2q3 \\ 2q0q2 + 2q1q3 & -2q0q1 + 2q2q3 & q0^2 - q1^2 - q2^2 + q3^2 \end{bmatrix} \tag{3}$$

The attitude angles can be calculated as:

$$\begin{cases} \psi = ac\tan((2q0q2 - 2q1q3)/(q0^2 + q1^2 - q2^2 - q3^2)) \\ \theta = ac\sin(2q0q3 + 2q1q2) \\ \gamma = ac\tan((2q0q1 - 2q2q3)/(q0^2 - q1^2 + q2^2 - q3^2)) \end{cases} \tag{4}$$

From accelerometer the roll and pitch are calculated by:

$$\begin{bmatrix} f_x \\ f_y \\ f_z \end{bmatrix} = C_n^b \begin{bmatrix} 0 \\ g \\ 0 \end{bmatrix} = \begin{bmatrix} g\sin\theta \\ g\cos\theta\sin\gamma \\ -g\cos\theta\cos\gamma \end{bmatrix} \tag{5}$$

Where fx, fy and fz represent the measures of the accelerometer in the a frame; and g stands for the gravitational acceleration. Then, the yaw and roll is:

$$\begin{aligned} \theta &= ac\sin\left(\frac{f_x}{g}\right) \\ \gamma &= ac\tan\left(\frac{-f_y}{f_z}\right) \end{aligned} \tag{6}$$

Similarly, for pitch:

$$\begin{bmatrix} H_x^l \\ H_y^l \\ H_z^l \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\cos\psi\sin\theta & \cos\gamma\cos\theta & \sin\gamma \\ \sin\theta\sin\gamma & -\sin\gamma\cos\theta & \cos\gamma \end{bmatrix} \begin{bmatrix} H_x^b \\ H_y^b \\ H_z^b \end{bmatrix} \tag{7}$$

Where H^b is the earth magnetic field in the a frame and H^l in horizontal Frame. Thus, the pitch is given by:

$$\psi = a\tan\left(\frac{H_z^l}{H_x^l}\right) + D \tag{8}$$

Where D is the distortion due to the magnetic components around the device. The calculated vector of gravitational field and electromagnetic field are obtained by:

$$\begin{cases} \hat{v}_g = \dfrac{\hat{g}^b}{\|\hat{g}^b\|} \\ \hat{v}_m = \dfrac{\hat{m}^b}{\|\hat{m}^b\|} \end{cases}, \begin{cases} \hat{g}^b = C_n^b({}_n^b q) g^n \\ \hat{m}^b = C_n^b({}_n^b q) m^n \\ g^n = [0 \quad 1 \quad 0]^T \\ m^n = [m_N \quad m_U \quad 0]^T \end{cases} \tag{9}$$

$$g^b = [a_x \quad a_y \quad a_z]^T \; and \; m^b = [m_x \quad m_y \quad m_z]^T \tag{10}$$

An AHRS system includes two separate functioning blocks. They are:

Two-Step Geometrically-Intuitive Correction

Figure 4 A TGIC the step wise two-step geometrically-intuitive corrective system is the method used to make the present approximation of pitch/roll invulnerable to magnetic distortions. It gives a calculated quaternion value for the Kalman filter, which does not give the linearization error of measurement equivalences and decreases the computational time.

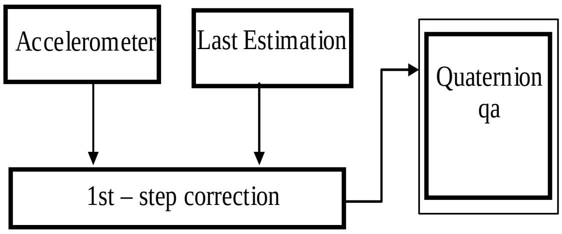

Figure 4: Block Diagram of TGIC's 1st Step.

Quaternions obtained from the Euler angles are passed to TGIC first step correction where the correction of projected track of gravity is done as shown in the Figure 5, correction for the assessed direction of gravity is done by spinning the least valued attitude quaternion q_k by the angle b (the angle in vg & vg) about the axis n_a (that is defined by the dot multiplication of vg & vg). Therefore, the matching error quaternion q_{ae} and calculated orientation q_a can be given by:

$$q_{ae} = \cos\left(\frac{\mu_a \Delta\theta_a}{2}\right) + \vec{n}_a \sin\left(\frac{\mu_a \Delta\theta_a}{2}\right) \tag{11}$$

$$q_a = q_{ae} \otimes q_k \tag{12}$$

Where,

$$\vec{n}_a = v_g \times \hat{v}_g, \Delta\theta_a = a\cos(v_g \cdot \hat{v}_g) \tag{13}$$

The variable 'c' is utilized to decrease the effect of the exterior acceleration. By partly modifying the angle c, the influence of outside acceleration will be found to be near to 0. The prime choice for 'c' is so that the system can produce a strong attitude in static and active tests, not overshooting. The calculation of the variable 'c' in many different situations will be shown in the experimentation section.

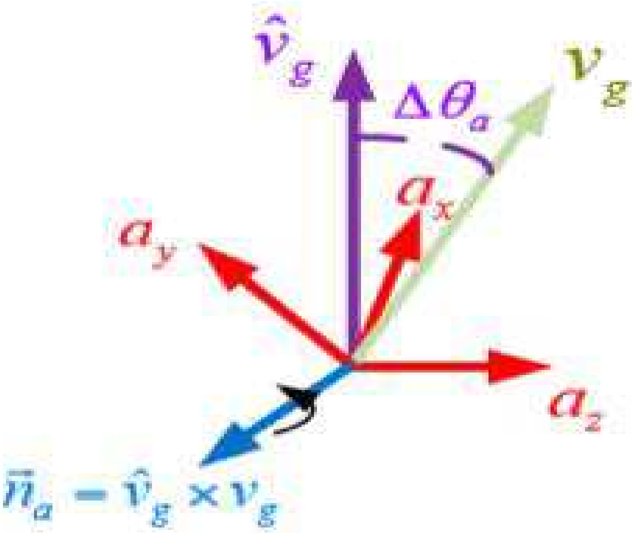

Figure 5: Correcting the Projected Direction of Gravity using the Accelerometer.

Ex-tended Kalmanian Filter

Under estimation theory, the ex-tended Kalmanian filter (EKF) is a non-linear form of the Kalmanian filter that linearizes around an approximation of the present average and covariance. In the conditions of a well- structured transition model, the EKF has been regarded as standard in the field of nonlinear value estimation, navigating systems and GPS system.[6] Accelerometer, gyro and mag values are taken from IMU GY80. TGIC consists of two steps to be followed.First step only includes the correction of accelerometer values and second step includes the correction of magnetometer values. The combined steps gives the calibrated roll, pitch and yaw values. The values are passed to the Extended Kalman filter in the form of quaternions where prediction and updating step are used to reduce the error. [3] The calculation of the theorized Kalmanian filter starts with in initial conditions:

$$\begin{cases} \hat{X}_0 = E[X_0] \\ P_0 = E\left[(X_0 - \hat{X}_0)(X_0 - \hat{X}_0)^T\right] \end{cases} \tag{14}$$

The original covariance matrix Po is permanently given a big positive number in order to attain a steady filter and it is calculated that Po = 10·I [3×3]. I [3×3] is the 4x4 identity matrix. The step next is to show the current vale and covariance approximations from time stamp k1 to step k2:

Where exp(Ω_kT) is the separate time stamp transition matrix; & Q_k is the process errorcovariance associated to the quaternion. Then, the Kalman gain is calculated as:

$$\begin{cases} \hat{X}^-_{k+1} = \exp(\Omega_k \Delta T) X_k \\ \hat{P}^-_{k+1} = \exp(\Omega_k \Delta T)\, P_k \exp(\Omega_k \Delta T)^T + Q_k \end{cases} \tag{15}$$

where R_{k+1} is the measurement noise covariance. The final thing to do is to calculate the post error covariance approximate:

$$K_{k+1} = \hat{P}^-_{k+1}\left(\hat{P}^-_{k+1} + R_{k+1}\right)^{-1} \tag{16}$$

where Z_{k+2} is the calculated quaternion. From the steps of the Kalmanian filter detailed above, we can attain the prime estimated quaternion and finally obtain the 3-D attitude of the aircraft. The quaternions from the second step i.e X_{k+1} is used to obtain the attitude (roll, pitch and yaw) as in equation (3).

AHRS Algorithm

The proposed AHRS in this paper is a predict and updating technique where we detect the error using Kalman Filter and estimating correct direction gravity using TGIC as mentioned in Figure5. First, we allow the calibration of the pitch, roll and acceleration of the IMU to take place for 5 seconds. We calculate the mean pitch angle, mean roll angle, mean yaw angle and mean magnetometer reading x, y, z directions. This mean pitch, roll and acceleration calculated are used as a reference for setting thresholds and to form a quaternion.

The sender and Receiver part of the procedure shown in Figure 6 as follows:

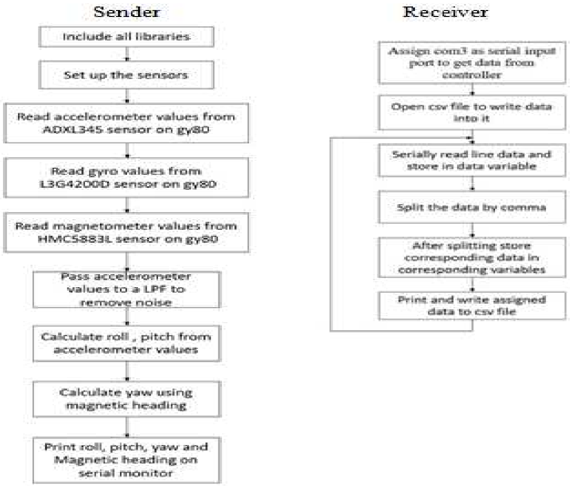

Figure 6: Flowchart of Sending and Receiving Data from Controller to Device.

Working of Extended kalman filter with TGIC is shown in the flowchart Figure7.

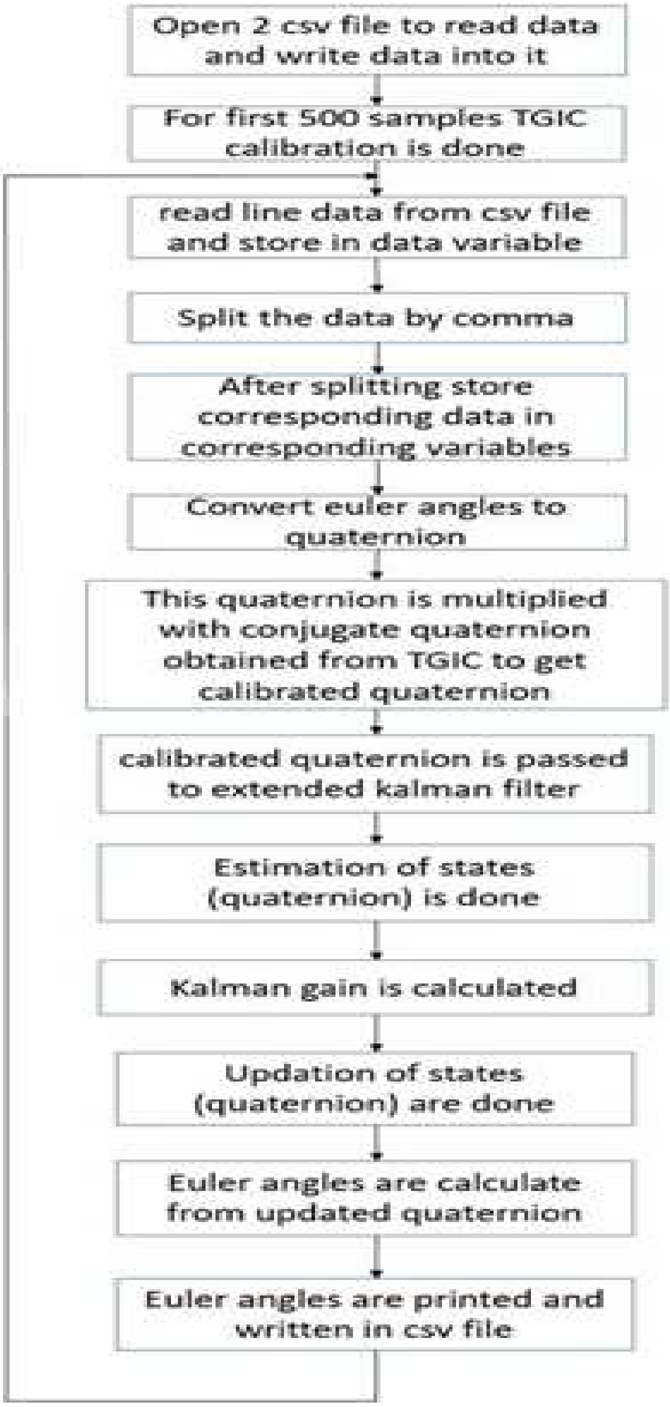

Figure 7: Flowchart of Kalman Filter with TGIC.

EXPERIMENTAION AND RESULT

Figure 8 shows the circuit set up. We first collect the data from the accelerometer, gyroscope and magnetometer of the GY-80. We first conduct an experiment where the IMU is placed stationary on a flat table and we get the raw roll, pitch, and yaw at a sample rate of 100Hz. We take the first 500 samples as calibration time and then the above data is passed through the algorithm and the result is shown. The plot of raw roll, pitch and yaw wise rotated data are shown in the following figures.

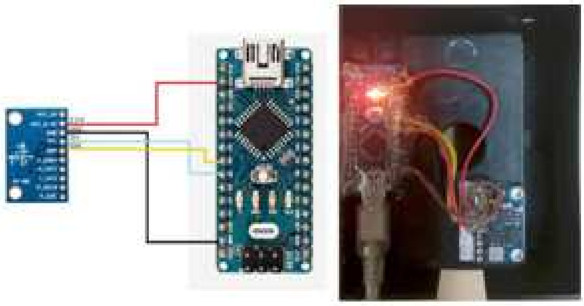

Figure 8: Circuit Diagram with Model.

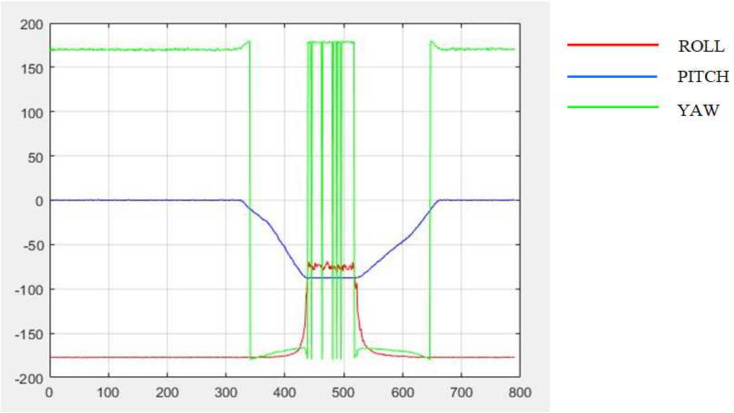

Figure 9: Plot of Raw PITCH wise Rotated Data (Degree).

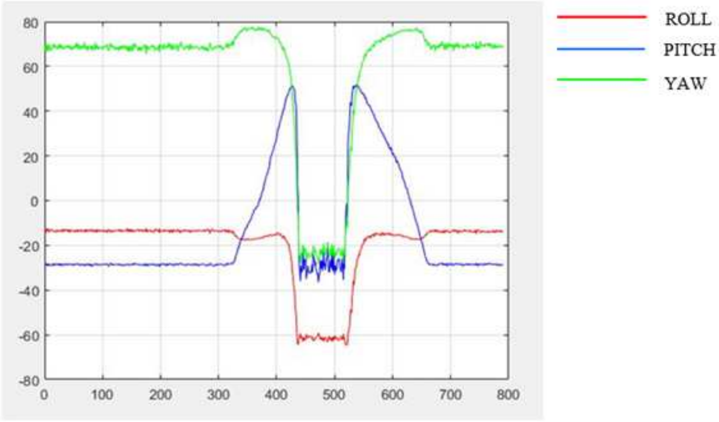

Figure 10: Plot of Estimated PITCH wise Data(Degree).

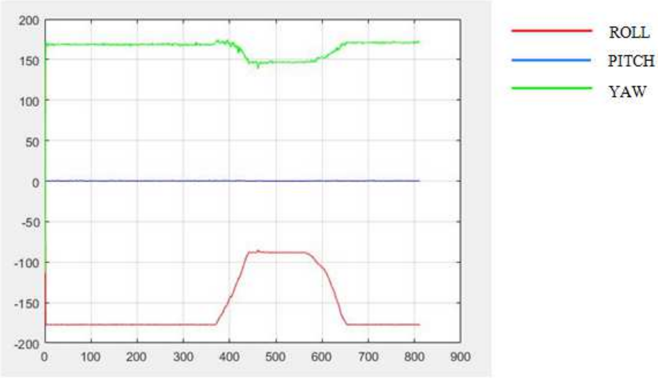

Figure 11: Plot of Raw ROLL wise Rotated Data (Degree).

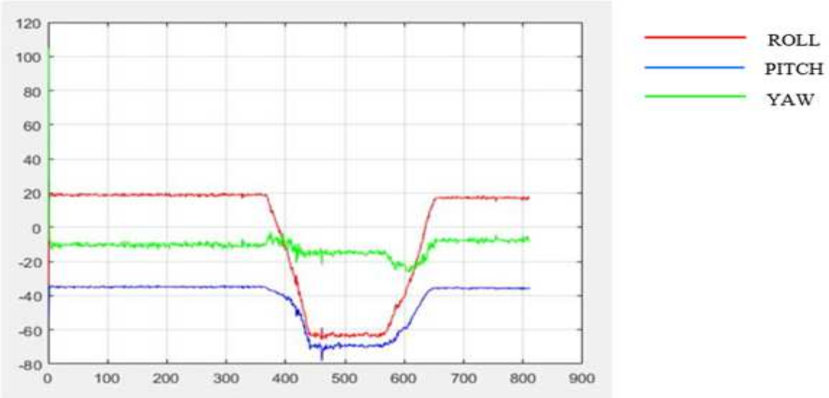

Figure 12: Plot of Estimated ROLL wise Data(Degree).

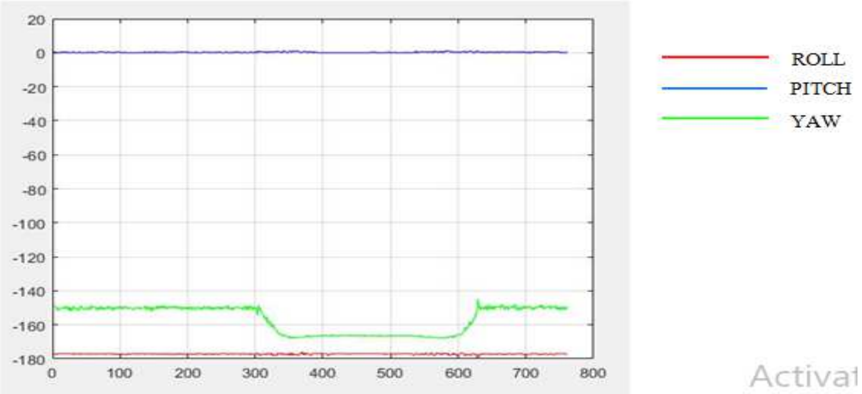

Figure 13: Plot of Raw YAW wise Rotated Data (Degree).

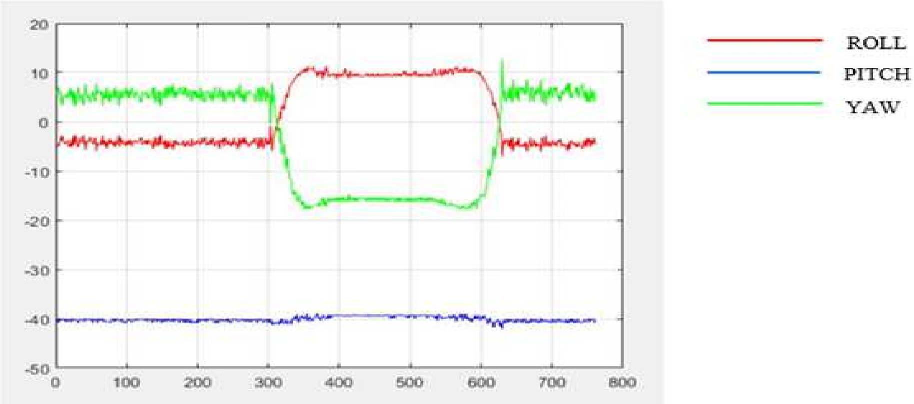

Figure 14: Plot of Estimated YAW wise Data(Degree).

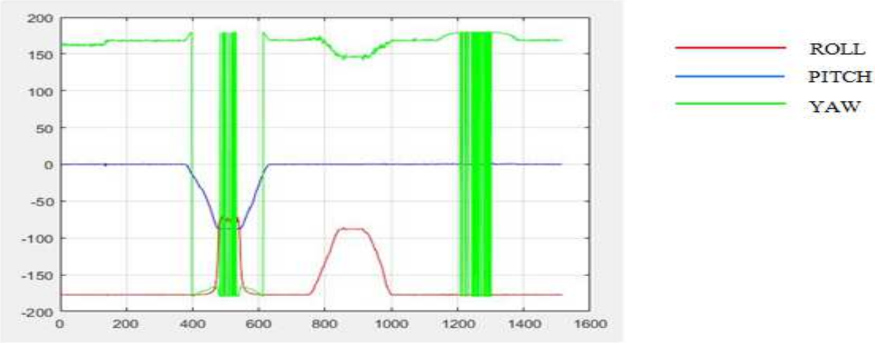

Figure 15: Plot of Raw PITCH, ROLL and YAW wise Rotated Data (Degree).

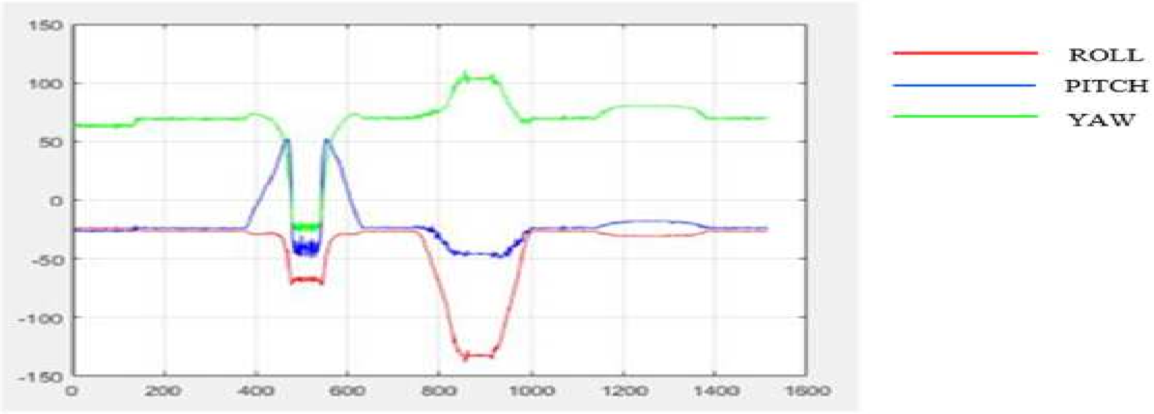

Figure 16: Plot of Estimated Pitch,Roll and Yaw wise Rotated Data Lot of Estimated Data(Degree).

CONCLUSIONS

In this paper, Extended Kalman filter was pro-posed for the orientation estimation of AHRS. The Kalman filter was significantly simplified by preprocessing the accelerometer and magnetometer information using a two-step geometrically-intuitive correction (TGIC) approach. Compared with the traditional external quaternion estimation algorithm, the use of two-step correction decouples the accelerometer and magnetometer information. Here we used only first step later with mag also can be implemented. This decoupling eliminates the influence of magnetic interference on the current estimation of pitch/roll. In addition, the quaternion produced by the TGIC is utilized as the input observation vector for the Kalman filter, which avoids the linearization error of measurement equations and reduces the computational complexity of the filter. By carrying out several experiments, the performance of the proposed filter in static and dynamic conditions was verified. The experimental results indicate that the proposed Kalman filter is able to provide relatively faster and more accurate real-time orientation information in different working conditions.

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