REAL TIME FILTER AND FUSION OF MULTI-SENSOR DATA FOR LOCALIZATION OF MOBILE ROBOT

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ABSTRACT

This project work presents the sensor fusion of Global Positioning System (GPS), Inertial Measurement Unit (IMU) and Odometry data from wheel encoders which is used to estimate localization of mobile robot. GPS, IMU, Wheel encoders are interfaced with MBED. Filters are used to remove erroneous noise from the data obtained from sensors. Low pass IIR filter is used for Differential Global Positioning System (DGPS) data, Complementary filter for IMU data. The project work discusses each of these approaches for Real time filtering of fusion of sensor in an Outdoor environment. The above Fusion algorithm is implemented on MBED Platform.

Keywords: Complementary Filter, Fusion, Localization, Low Pass IIR Filter, Outdoor Environment.

I. INTRODUCTION

Sensor fusion concerns several field of research including multiple sensors like GPS, IMU, Wheel encoders. For the Outdoor mobile Robot to estimate the localization DGPS is used for improved accuracy. It is not sufficient to make use of only DGPS, as DGPS runs on Line of Sight (LoS), for better accuracy fused data from GPS, IMU and Odometry is preferred.

In earlier days Researchers make use of only GPS, as it was giving erroneous noise and rapid fluctuation in localization [1] [8], later they came up with an idea of DGPS, in which two GPS were used, one GPS is placed on ground reference (reference point) and the other GPS was placed on robot. For Localization estimate with the help of GPS modules, Zigbee (XBEE Company) protocol is preferred which is according to the design requirement. IMU plays a vital role in order to determine
localization by means of estimating roll, pitch and yaw which will be given by tri-axial gyroscope, tri-axial accelerometer and magnetometer. In this project IMU has 9 Degree of Freedom (DOF) [2].

Wheel encoders (Odometry method) are used to determine the wheel speed and are used to control the speed of mobile robot. Localization of mobile robot is calculated by making use of encoder counts. Encoder counts are similar to PWM. Encoder counts are provided by Maxon DC motor which is mounted onto DC motor which is required for rotation of the wheel. In general, localization of mobile robot navigation in outdoor environment GPS, IMU and odometry data is incorporated in the design. These are entirely self-contained within the robot in the sense that they are not dependent on the transmission of signals from the robot or reception from an external source. Inertial sensors measurements are independent of robot physical parameters. However, inertial navigation systems do rely upon the availability of accurate knowledge of robot position at the start of the navigation.

There are several approaches for estimating localization and many has been proposed by various researchers in the field of robotics till today. One method of estimating localization is by making use of Ultrasonic positioning systems and infrared network systems which are available at low cost, small, and can be easily interfaced. However, if the distance is too large it lags in accuracy due to signal interferences, hence nowadays not preferred. Another method proposed was RFID, which requires additional equipment; RFID requires high cost to implement. Global Positioning System (GPS) cannot be used in indoors and it has a slow update rate of approximately one second. So, researchers have come up with a new idea of using Differential GPS which will provide accuracy up to centimetre and are commercially available making them attractive for localization of outdoor mobile robots navigation [2] [3].

University of Michigan Benchmark (UMB) test is necessary as we have included Differential drive for the mobile robot, there may be slight errors due to systematic errors and non-systematic errors. To overcome it is necessary to calibrate the differential wheel by UMB mark test. Here mobile robot is made to move in a square pattern for estimating corner axis, by this way calibration is done by adding correction factor in the program [4].

Initial position is assumed as $X_0$, $Y_0$, $Z_0$

\[
\dot{X}_x = X_{absc} - X_{calc} 
\]  

(1a)
\[ \varepsilon_y = Y_{\text{abs}} - Y_{\text{calc}} \quad (1b) \]

\[ \varepsilon_z = Z_{\text{abs}} - Z_{\text{calc}} \quad (1c) \]

where,

\( \varepsilon_x, \varepsilon_y, \varepsilon_z \) are positional errors due to Odometry.

\( X_{\text{abs}}, Y_{\text{abs}}, Z_{\text{abs}} \) are absolute position and orientation of mobile robot

\( X_{\text{calc}}, Y_{\text{calc}}, Z_{\text{calc}} \) are position and orientation error of the robot as computed from odometry data.

Center of gravity in clockwise direction is given by,

\[ r_{cg,\text{cw}} = \sqrt{(X_{cg,\text{cw}})^2 + (Y_{cg,\text{cw}})^2} \quad (2a) \]

Center of gravity in anti-clockwise direction is given by,

And

\[ r_{cg,\text{ccw}} = \sqrt{(X_{cg,\text{ccw}})^2 + (Y_{cg,\text{ccw}})^2} \quad (2b) \]

II. VARIOUS FILTER ALGORITHMS

Design

A. Low pass IIR filter

Infinite Impulse Response (IIR) is used to filter out rapid fluctuation of the GPS data and used to suppress erroneous noise. Setting up the coefficient for both input and output is the preliminary requirement; it all depends on the order of the system. Choosing the gain coefficient ‘\( \alpha \)’ plays a vital role in the design aspect.

\( 0 < \alpha < 1 \)

Circuit complexity is dependent on order of the system.

For \( n^{th} \) order system, output \( y[n] \) is given by,

\[ y[n] = \frac{1}{a_0} (b_0 x[n] + b_1 x[n - 1] + \cdots + b_p x[n - p] - \frac{1}{a_1} (a_1 y[n - 1] - a_2 y[n - 2] - \cdots - a_q y[n - q]) \]

\[ (3) \]

Where:

‘\( p \)’ is the feed forward filter order

\( b_0 \) is the feed forward filter coefficients

‘\( q \)’ is the feedback filter order

\( a_0 \) is the feedback filter coefficients

\( x[n] \) is the input signal

\( y[n] \) is the output signal.

\[ \sum_{j=0}^{q} a_j y[n - j] = \sum_{i=0}^{p} b_i x[n - i] \]

Transfer function \( H(Z) \) of the system is given by,
\[
H(Z) = \frac{Y(Z)}{X(Z)} = \frac{\sum_{i=0}^{p} b_i x[n-i]}{\sum_{j=0}^{q} a_j y[n-j]} \quad (4)
\]

For 1\textsuperscript{st} order system, output of the low pass Infinite Impulse Response (IIR) filter equation is given by,

\[
b[i] = (1-\alpha)b[i-1] + \alpha (c[i] - b[i-1]) \quad (5)
\]

where,

- \(b[i]\) = present output
- \(b[i-1]\) = previous output
- \(\alpha\) = gain parameter
- \(c[i]\) = present input

Data obtained from GPS (latitude, longitude and altitude) are substituted in eqn.6 or in eqn.7 and then the updated value is used in eqn.5. Eqn.5 determines the gain quantity which is dependent on both input and output. ‘\(\alpha\)’ on input and ‘1-\(\alpha\)’ on output.

From the first GPS latitude1, longitude1 and altitude1 data are extracted, these data are converted into XYZ coordinates with the help of eqn.6,

\[
X1 = R \cos(\text{latitude1}) \cos(\text{longitude1}) \quad (6a)
\]
\[
Y1 = R \cos(\text{latitude1}) \sin(\text{longitude1}) \quad (6b)
\]
\[
Z1 = R \sin(\text{altitude1}) \quad (6c)
\]

And from the second GPS latitude2, longitude2 and altitude2 data are extracted, these data are converted into XYZ coordinates with the help of eqn.7,

\[
X2 = R \cos(\text{latitude2}) \cos(\text{longitude2}) \quad (7a)
\]
\[
Y2 = R \cos(\text{latitude2}) \sin(\text{longitude2}) \quad (7b)
\]
\[
Z2 = R \sin(\text{altitude2}) \quad (7c)
\]

First MBED sends GPS data (latitude, longitude and altitude) to second MBED via Zigbee protocol. Since, we are using DGPS. We take the difference of second GPS coordinates with the first GPS coordinates in order to estimate XYZ coordinate. Localization of mobile robot considering localization from set of eqn.6 and eqn.7 with respect to reference point is given by,

\[
X_{\text{diff}} = X2 - X1 \quad (8a)
\]
\[
Y_{\text{diff}} = Y2 - Y1 \quad (8b)
\]
\[
Z_{\text{diff}} = Z2 - Z1 \quad (8c)
\]
Baud rate of both MBED micro controller are set to 9600 for GPS communication and 57,600 for IMU and Odometry communication. In GPS module, if lock is enabled we can able to fetch localization readings.

B. Complementary filter

IMU measures accelerations and rotation rates, and possibly earth’s magnetic field in order to determine a body’s attitude. The complementary filter fuses the accelerometer and integrated gyro data by passing the former through a first order low pass and the latter through a first order high pass filter and adding the outputs [6].

The transfer function can be represented by,

\[ \theta = \frac{1}{1+T_s} \alpha + \frac{T_s}{1+T_s} \frac{1}{s} w = \frac{\alpha + T_w}{1+T_s} \]  

(9)

This determines the filter cut-off frequencies.

Using backward difference yields

\[ 1+T_s = \left(1 + \frac{T}{\Delta T}\right) - \frac{T}{\Delta T} z^{-1} \]  

(10)

On substituting (2) in (1), we get

\[ \theta_k = \alpha(\theta_{k-1} + w_k \Delta T) + (1 - \alpha) \alpha_k \]  

(11)

Where, \( \alpha = \frac{T}{\Delta T (1 + \frac{T}{\Delta T})} \)

On simplifying, we arrive at an expression

\[ \theta_k = \alpha \theta_{k-1} + (1 - \alpha) \alpha_k + \alpha w_k \Delta T \]  

(12)

III. IMPLEMENTATION DESIGN

GPS makes use of Heading measurements, GPS module (from Nex Robotics) is connected to MBED- ARM Micro Controller, GPS receives around 5 sets of data stream continuously ($GPGGA$, $GPGSA$, $GPGSV$, $GPRMC$, $GPVTG$), here $GPGGA$ is preferred as it gives the information regarding latitude, longitude and altitude, N/S, E/W direction [1]. By which we can convert the obtained data into XYZ co-ordinate systems as mentioned in low pass IIR design. As we know that GPS is erroneous to noise and accuracy is also poor, hence Differential GPS (DGPS) is preferred. As two GPS modules are not connected to same MBED, so for communicating between two MBEDs we make use of Zigbee protocol (XBEE Company) is preferred which supports wireless communication.

IMU includes tri-axial accelerometer (from Analog devices), tri-axial gyroscope (from Invensense) and magnetometers (from Honey well). All three sensors are interfaced with Atmega328 µc assembled by spark fun (company) [7].

Yaw angle, \( \psi = \varphi + \lambda \)

and \( \varphi = \tan^{-1}\left(\frac{H_x}{H_y}\right) \)

where,

\( \psi = \) yaw angle

\( \varphi = \) magnetic angle of inclination
\[ \lambda = \text{angle of declination} \]
\[ H_x = \text{Magnetic field along 'x' axis} \]
\[ H_y = \text{Magnetic field along 'y' axis} \]

Localization of the robot from wheel encoders as a vector with the three elements \((x, y, \text{direction and pitch})\)

\[
P_{xy} = \begin{bmatrix} x \\ y \\ \theta \end{bmatrix} \quad (13)
\]

The mapping is accomplished using the orthogonal rotation matrix:

\[
R(\theta) = \begin{bmatrix} \cos \theta & \sin \theta & 0 \\ -\sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (14)
\]

This matrix can be used for localization \(x, y\). This operation is denoted by \(R(\theta)P_{xy}\) because the computation of this operation depends on the value of pitch\((\theta)\)

\[
P_{xy} = R(\theta)P_{xy} \quad (15)
\]

**IV. SIMULATION RESULTS**

Simulation Results are extracted using Matlab. With the help of odometric data, we localize the corner points of the mobile robot. Since, there is slight variation in the initial and final position of mobile robot, when the robot navigates over a square path. Thus correction factor is included in the programming part, and the state space is as shown in figure 3.

![Figure 3 UMB mark calibration space points](image_url)

Mobile robot is moved in outdoor environment and localization points are noted down in Matlab and are simulated to obtain the plots.
Figure 4 3-D plot of localization along XYZ axis with respect to time

Figure 4 describes the localization along X, Y, Z axis with filter and without filter. The gain ‘α’ what I have chosen is 0.5. Gain (α) is the fraction of quantity depending on input, and (1-α) is the fraction of quantity depending on previous output.

Figure 5 Robot in motion, Roll measurement

Figure 6 Robot in motion, Yaw measurement
When the robot is navigating in the inclined surface it will experience roll and pitch variation. These rapid variation will result in overestimation and underestimation of robot’s position. Although when the robot moves in an inclined plane, its movement should be similar to its movement in ground plane. To achieve this in an efficient way we have incorporated IMU as shown in fig 5, fig 6 and fig 8.

![Figure 7 Robot in motion, Pitch measurement](image)

![Figure 8 Navigation in X-direction experiencing pitch](image)

V. CONCLUSION AND FUTURE WORK

The proposed filter algorithm for GPS, IMU offers fast and accurate attitude estimation. Position estimation is inaccurate due to integration factor. Complementary filter is incorporated in attitude estimation wherein angles from accelerometer, magnetometer on one side and gyroscope on other side are fused, is not only simple in implementation but also consumes less computation unlike Kalman filter algorithm. The robot during navigation has also accounted for the deterioration of actual position traversed. The most accurate and reliable value is yaw angle, mainly because of magnetometer, which made it possible to eliminate drift. In order to improve the localization of mobile robot in outdoor environment or uneven terrain furthermore, we should incorporate multi-sensors (camera, pressure sensor etc) fusion of multi-sensor data has to be considered for better localization estimation.
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REFERENCES