Magnetometer-based full Attitude Update (MAU) for frame misalignment correction in Pedestrian Dead Reckoning (PDR)

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Pedestrian navigation is one of the most challenging navigation problems. This is due to the high dynamics of pedestrian motion and its variability from one user to another, in addition to the low integrity of GNSS in environments where day-to-day activities occur; such as indoors. Advancements in Micro-Electro-Mechanical Systems (MEMS) technology has led to the integration of low-cost MEMS Inertial Measurements Units (IMU) in nearly all smart devices, including smartphones. The MEMS-based inertial sensors typically used in smartphones suffer from high noise and errors, that tend to make them unreliable for long-time navigation using the conventional methods such as Dead Reckoning (DR). other techniques; such as Pedestrian Dead Reckoning (PDR), try to overcome the errors in the DR by breaking down the user's travelled distance into sequence of steps and an estimated stride length in a certain direction.

For reliable PDR navigation, accurate estimation of the misalignment between the navigation frame and sensor body frame is needed. Misalignment errors reflect on the accuracy of the navigation drastically as it leads to: wrong elimination of gravity component from accelerations, and wrong estimation of heading. The wrong elimination of gravity components leads to wrong estimation of travelled distance based on estimated stride length, while the wrong estimation of heading adds up to the position error, as it accumulates distance moved in the wrong direction. Both errors lead to the short-term accuracy of the inertial navigation systems.

This paper presents a new algorithm for correcting the misalignment between the sensor/body frame and the Local Level Frame (LLF) also referred to as navigation frame. This is done through the use of magnetic measurements M_b, and the available information about earth magnetic map from the World Magnetic Map (WMM) M_{llf}. An Extended Kalman Filter (EKF) is used to correct the errors in the estimated platform attitudes – roll, pitch, and azimuth – based on the errors observed from aligning the magnetometer measurements from the body frame to LLF. Under the assumption of low magnetic perturbations, the transformation matrix R_b^{llf} from body frame to LLF should yield a magnetic vector that is nearly equal to the reported magnetic field M_{llf} obtained from the WWM.

$$M_{llf} \cong \widehat{M}_{llf} = R_b^{llf} * M_b$$

Errors in estimated attitudes will yield higher than expected differences between the estimated magnetic field in LLF and the reference magnetic field provided by the WMM. These differences between the estimated and the reference magnetic components in LLF is a function of the errors in attitudes, and can be used to correct the estimated attitude states.

Furthermore, in a quasi-static magnetic field over a period of time – even if the magnetometer measurements are attenuated by other magnetic sources that are static over a period of time – the same method can be used to correct the errors in attitudes.

This work also presents means of verification of corrected attitudes through the introduction of a third reference frame that is known as the Magnetic Frame (MF). The conventional navigation process relates the body frame directly to the navigation frame in a three rotational sequence depicted by the Direction Cosine Matrix (DCM). In this work, we assume an intermediate frame which is the magnetic frame. This frame is characterized by having the vertical axis aligned with the magnetic vector obtained from the WMM depending on the user's location. This is similar to how the navigation frame is aligned with the gravity vector.

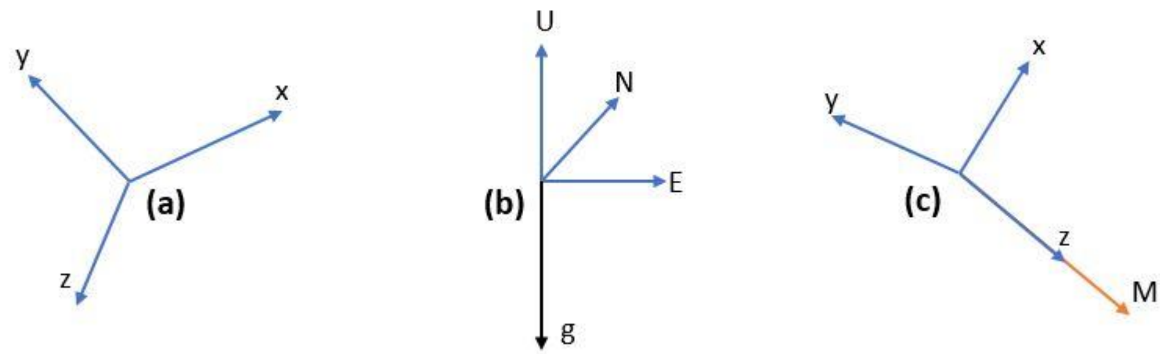

Figure 1 Coordinate frames: (a) BF, (b) LLF , (c) MF

The underlying assumption is that the misalignment between the navigation frame and the magnetic frame can be achieved in the same manner as the initial alignment of mechanization-based Inertial Navigation System (INS). That is, a roll and pitch angles relating the two frames can be computed using simple trigonometric functions. It is important to note that the magnetic frame is nearly static and only changes slightly over time. Hence the alignment is not carried out regularly. Using a constructed DCM between the navigation and magnetic frames, the gravity components are known in the magnetic frame.

The verification process is carried out through the use of a three rotation sequence that is based on the MF in comparison to the transformation matrix relating the body frame and the LLF. The three rotations sequence is composed of the rotation matrix transforming LLF to MF, the transformation matrix that relates BF to MF, and a third rotation matrix around the z-axis of the MF.

$$\hat{R}_{llf}^{b} \cong R_{M}^{b} * R_{Z(A)} * R_{llf}^{M}$$

Where (A) is an ambiguity heading angle in the magnetic field that is estimated to minimize the difference between the rotation sequence and the estimated direct transformation matrix. And the corrected attitudes are accepted if the difference between the corrected attitudes and the attitudes derived from the three rotations sequence is below a computed threshold.

The proposed methodology works on an epoch-by-epoch manner and resets the attitude angles obtained from the attitude mechanization of the gyroscope measurements, hence providing correction whenever the conditions apply. Direct frame alignment using the acceleration when it tends to gravity and magnetic vector as it tends to the reference would also result in attitude angles estimation, but the acceleration components will have greater effect on the resulting alignment. By using the proposed magnetic-based attitude correction in the EKF, the errors in the attitudes are estimated and are verified using the intermediate frame alignment proposed.

The proposed methodology has been tested using static data from smartphones, where the initial alignment was computed, and a full inertial and attitude mechanization was used to obtain the position and attitude of the device. The magnetic-based attitude correction EKF was used to verify the accuracy of correction under low magnetic perturbation. Dynamic simulated data with introduced noise was also used for testing. Preliminary results show the feasibility of obtaining attitude angles on epoch basis using the developed method, where the attitudes provided by the method are considered as corrections, and attitude mechanization is then employed until correction conditions are met. Results show that over short time periods of non-reliable magnetic measurements – 15 seconds –, when reliable measurements are available and the methodology is applied, the errors in the attitudes are enhanced to within ±0.25°

More tests are to be carried out in different phone orientation placement during walking. The expected results are that they would be the same as the ones obtained so far. The major factor that would affect the performance of this method is high magnetic fluctuations for long periods, resulting in not satisfying the conditions for applying the correction and relying on the attitude mechanization alone for attitude angle computation.

In conclusion, the proposed method can keep track of the misalignment between the body and navigation frames by providing attitude corrections on regular basis to aid the attitude mechanization. This is achieved through the use of magnetic measurements and knowledge of the reference magnetic field at any given point on earth at any given time provided by the WMM.

The significance of this work is that it attempts to eliminate the accumulated errors in pedestrian navigation over time from the integration of measurements over time which in turn will give a better estimation of the pedestrian position. The proposed algorithm is to be integrated with a full PDR system with the capability of step detection and stride length estimation for obtaining a full navigation state.