Deep Learning Aided Sensor Fusion for Drift Reduced IMU Orientation Estimation

Rahul Verma
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Supervisor: Dr Zhiqiang Zhang

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University of Leeds

Abstract

Inertial Measurement Units (IMUs) are widely used in a variety of applications such as Body Sensor Networks (BSNs) for orientation estimation, however the gyroscope suffers from drift due to sensor bias and noise that when integrated accumulate over time. This project investigates a deep learning-based approach which aims to mitigate gyroscopic errors which can be integrated with sensor fusion techniques to achieve more accurate orientation estimates. The proposed deep-learning architecture leverages both neural networks and a temporal history to learn complex and nonlinear error patterns in IMU data, exploring if it outperforms a standard Kalman Filter without learned corrections. The network outputs a correction for the incoming gyroscope sample and ad the measurement noise covariance dependent on the incoming acceleration and magnetometer updates. The data used in training, testing and validating the model come from simulations through MATLAB's Navigation Toolbox and from public datasets such as Berlin Robust Orientation Estimation Assessment Dataset (BROAD).

Acknowledgements

I would like to express my sincere gratitude to Dr. Zhiqiang Zhang for his continuous support and guidance throughout this project. Dr. Zhang's insights and advice during this project, in particular the quaternion algebra and an indepth explaination of filters were invaluable in shaping the direction of my work. In addition, offering his personal copy of Body Sensor Networks to aid in my understanding is highly appreciated.

I would also like to acknowledge the authors and maintainers of the publicy available datasets of BROAD and RepoIMU. Their efforts in collecting and labelling high quality IMU data and optical motion capture ground truth enabled the training, testing, and validation of the neural network. I am grateful for their contributions and cite them accordingly in this report.

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1 Introduction

1.1 Inertial Measurement Units (IMUs) and their applications

IMUs are composed of multiple sensors which include a gyroscope, accelerometer, and occasionally a magnetometer. These three sensors measure the angular rate, linear acceleration, and the local magnetic field vector respectively. These measurements can be used to estimate the orientation of an object through integration of the angular rate. This data acquisition is essential for several applications such as BSNs **FIXME:** cite, robotics, and autonomous vehicles where these systems rely on high-rate orientation updates.

IMUs have emerged as a key technology due to the ability to work in a self- contained environment. In environments where external references of orientation are unavailable or unreliable, technologies such as IMUs are attractive. Filters, such as the Kalman filter, allow the use of accelerometers and magnetometers to guide and correct state estimation, but these also suffer from failures like magnetic disturbances and high linear accelerations corrupting a gravitational reference. Due to these limitations, there is significant motivation to explore data-driven methods that compensate for these conditions and errors.

WORDS: 170

1.2 Problem Statement: IMU Drift and Its Impact

IMUs have shown promise in determining the orientation of an object in motion. However, IMUs suffer from a limitation called drift. IMU drift is characterised by the accumulation of errors through the integration of the angular rate. The sources of these errors include constant bias, scale factor errors and others expanded in section 3.1.2. Errors are not exclusive to the gyroscope but also affect the accelerometer and magnetometer. Drift is also dependent on the type of IMU that is used. Lower cost/grade IMUs suffer from drift at a higher magnitude which results orientation inaccuracies much quicker compared to higher cost/grade IMUs. Errors then lead to inaccuracies in the orientation estimation of an object determined by the IMU.

Kianifar et al. explored using IMUs for automated orientation estimation in a clinical setting. They found that for rotation angles parallel to gravity, drift due to gyroscope bias cannot be compensated by the accelerometer.**FIXME:** cite. Even with multiple sensors, it is still challenging to find an accurate orientation estimation. Thus it is important to try and address the orientation problem by addressing gyroscopic drift.

Therefore, this project aims to address gyroscopic drift by using deep-learning methods to learn complex and non-linear nature of biases and errors.

WORDS: 211

1.3 Research Question and Hypotheses

The question this project aims to answer is: **Can Deep Learning be used to learn the drift pattern to get drift free orientation estimation?** While this is the overarching question, it can be broken down to the following:

- How effectively can deep learning learn the drift experienced?
- Can this model be generalised or will the model only apply to a single dataset?
- What are the advantages or disadvantages of using Deep Learning compared to traditional approaches?

The hypothesis that I state is that the by incorporating a deep-learning model, we will be able to see a percentage decrease in the orientation error over a period of time.

2 Deep Learning Drift Mitigation: Literature Review

3 IMU Basics and Operational Principles

As mentioned before, IMUs consists of tri-axial gyroscope, accelerometer, and magnetometer. They measure angular rate, specific force, and the local magnetic field vector. The sensors are mounted so that it measures their components in the three orthorgonal axes x^b, y^b, z^b.

3.1 Gyroscope: Operations and Errors

The gyroscope is the main component that is used to determine the orientation of the object. It measures the angular rate in its orthorgonal axes $\omega^x, \omega^y, \omega^z$ which is used to determined the object's orientation at a discrete time. The orientation is determined through the integration of angular rate. There are multiple different ways to represent the orientation of the object, these being, Euler angles, rotation matrices, and quaternions. Euler angles give rise to the singularity problem due to the loss of one degree-of-freedom whenever two axes of the rotations are parallel **FIXME:** cite. Rotation matrices are also used, however they are less concise as they are represented as 3x3 matrix, where 6 of these elements are redundant**FIXME:** cite. Therefore in this chapter, the quaternion representation is selected due to being more computationally efficient than the others **FIXME:** cite prof paper.

3.1.1 Angular Rate Integration

Starting in continuous-time kinematics, we can define a quaternion that is represented by the angular rate, where ω is the real angular rate, $\omega_q(t)$ is the pure quaternion.

$$\omega_q(t) = [0,\ \omega_x(t),\ \omega_y(t),\ \omega_z(t)] \tag{1}$$

The orientation evolves according to**FIXME:** cite

$$\dot{q}(t) = \frac{1}{2} q(t) \otimes \omega_q(t) \tag{2}$$

where $\otimes$ denotes quaternion multiplication. The solution over $[t_0, t]$ can be written using the quaternion exponential, this assumes that the ω_q is constant over τ.

$$q(t) = q(t_0) \otimes \exp\left(\frac{1}{2} \int_{t_0}^{t} \omega_q(\tau)\, d\tau\right) \tag{3}$$

These equations show that the orientation update is determined by integrating the angular rate over time and mapping the resulting rotation into a quaternion via the exponential.

Moving to discrete-time kinematics, we can restate of defintions in terms Δt. Here the orientation evolves according to

$$\hat{q}_k = \hat{q}_{k-1} \otimes \Delta q_k \tag{4}$$

where Δq_k is

$$\Delta q_k = \exp\left(\frac{1}{2} \omega_{q,k} \Delta t\right) \tag{5}$$

This was all done by using an ideal ω_k, if were to model the angular rate from a gyroscope as **FIXME:** cite

$$\omega_{m,k} = \omega_k + b_k + n_k \tag{6}$$

Where $\omega_{m,k}$ is the measured angular rate, ω_k is the true angular rate, b_k is the bias term, and n_k is the noise term. The real quaternion orientation update is as follows.

$$\hat{q}_k = \hat{q}_{k-1} \otimes \exp\left(\frac{1}{2} (\omega_k + b_k + n_k)_q \Delta t\right) \tag{7}$$

This shows that the inclusion of the bias and noise accumulates over samples as we move forward to the next k, q_{k-1} will incorporate the previous error terms. This results in an accumulated orientation error.

3.1.2 Gyroscope Error Sources

Constant Bias

The bias of a gyroscope is the average output from the gyroscope when it is not undergoing any rotation **FIXME:** cite. This is measured in $^\circ/h$ and can be estimated by taking an average of the output. As this bias is constant, the drift it causes grows linearly with time. However, as discussed further in this section other error sources can make this difficult to determine. **FIXME:** Figure shows how constant bias changes the output.

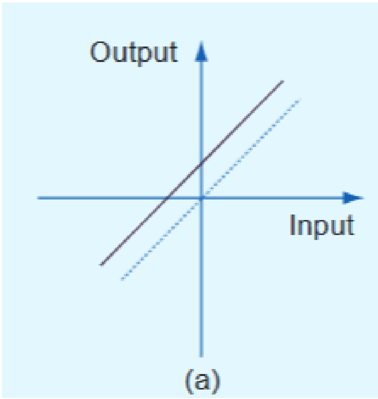

Figure 1: Bias Effect on Gyro **FIXME:** cite

White Noise / Angle Random Walk (ARW)

The gyroscope is also affected by some white noise **FIXME:** cite. This white noise sequence is zero-mean uncorrelated random variables between samples and across axes. When the gyroscope signal is integrated to obtain an angle, this white noise produces an ARW. The units of ARW is denoted by $^\circ/\sqrt{h}$, this shows that the deviation of angle error grows proportionally to $\sqrt{t}$. As ARW is due to random variables, it is classified as the 1σ of the orientation error. Analog devices shows this in the **FIXME:** figure, where the ARW is $0.17^\circ/\sqrt{h}$.

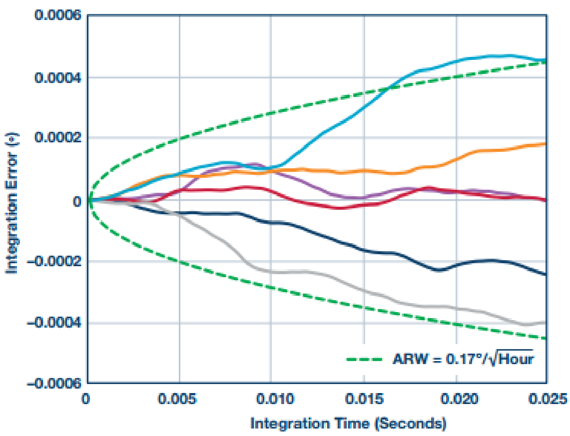

Figure 2: Effect of ARW on Gyro Output **FIXME:** cite

Flicker Noise / Bias Stability

The gyroscope suffers from flicker noise in electronics **FIXME:** cite Flicker noise is $1/f$, due to this the effects are observed at lower frequenices while, higher frequenices the noise is dominated by white noise.

Temperature

Temperature fluctuations due to changes in the environment and sensor heating induce a movement in the bias, this relationship is also highly non-linear **FIXME:** cite. Therefore, it can be very difficult to model and subsequently subtract from the gyroscope measurements compared to a constant bias.

3.2 Accelerometer: Operations and Errors

The accelerometer is another component used in determining an orientation estimate of an object. It measures the specific force along its orthogonal axes a^x, a^y, a^z. These measurements can be rotated in the navigation frame, gravity vector is compensated, and through integration of the accelerometer, a velocity and subsequently the position can be derived for an object. However, the focus of this project is to achieve drift-free orientation, and hence this will not be covered.

The main purpose of the accelerometer is to offer a gravity reference to the system such that, an accelerometer is capable of providing drift-free inclination estimates **FIXME:** cite. However, the accelerometer, as stated above, does not only measure a gravity reference but also any linear accelerations that the object also experiences. Under conditions of high accelerations, the reference is unreliable and is only reliable for static or slowly moving objects **FIXME:** cite. Additionally, the accelerometer cannot detect rotations about the gravity vector, so it cannot provide a yaw/heading of the object. However, like the gyroscope, it also suffers from a variety of errors which causes instability in the output.

3.2.1 Accelerometer Error Effects

Accelerometers suffer from a very similar sources of errors to the gyroscope (section 3.1.2). Therefore, in this section we will discuss the implications of these errors for our orientation estimates.

Constant Bias

The effect of constant bias is that it causes an offset in the roll/pitch of the system. Unlike constant bias in the gyroscope, it does not grow linearly with time but is a constant offset irrespective of time elapsed.

High Linear Acceleration

As discussed above, the largest problem is high linear accelerations which corrupts the gravity reference. This is a dominant issue in high dynamic motions as the accelerometer will not be able to correct the orientation estimation through fusion **FIXME:** section, especially if gyroscopic drift is not addressed.

A potential plan to address this will be discussed in **FIXME:** section

3.3 Magnetometer: Operations and Errors

Magnetometers measure the local magnetic field along its orthogonal axes m^x, m^y, m^z. While the accelerometer can help in determining the inclination (roll/pitch), of an object, it cannot observe any rotations along the gravity vector. This is where a magnetometer can be used to determine the heading (yaw) of an object. Sensor fusion/filtering algorithms are dependent on sensing the local magnetic flied to eliminate drift in the azimuth (yaw) portion of orientation estimates **FIXME:** cite. It does this by assuming that the measured local field vector provides a reference relative to Earth's field, however changes in the local field due to other field sources, can distort this measurement and gives rise to erroneous heading corrections.

3.3.1 Magnetometer Error Sources and Effects

Hard Iron/ Soft Iron

Hard Iron is a constant additive magnetic field applied to the sensor due to the interaction of magnetic fields **FIXME:** cite 2. An example of this can be a permanent magnet near the magnetometer interacting with Earth's field. This interaction between these sources leads to a constant vector being applied to the measurement. Whilst this constant vector is easy to subtract in theory, it is very difficult to measure the Earth's field ,in the local frame, without any interference of any kind.

Soft Iron are the effects generated by the interaction of an external magnetic field on any ferromagnetic materials near the sensor **FIXME:** cite 2. The resulting magnetic field depends on the magnetic field vector with respect to the orientation soft iron material **FIXME:** cite 3. This effect is difficult to determine as if the orientation of the sensor changes, then the orientation with respect to the soft iron also changes which distorts the field in a different way.

Noise

As previously stated, in each sensor there is some noise that will either arise from flicker noise or noise at higher frequencies which are modelled as white noise in nature. However, like the accelerometer, we do not need to do any type of integration which would lead to this noise giving an unbounded drift. Therefore, even though it is an error source any hard/soft iron effects would dominate any effect that noise would have on the system.

4 Deep Learning Architecture

5 Data: Training, Testing, and Validation

6 Conclusion and Next Steps