Optimization of Gyroscope and Accelerometer/Magnetometer Portion of Basic Attitude and Heading Reference System

Simone A. Ludwig
North Dakota State University
Fargo, ND, USA
simone.ludwig@ndsu.edu

Antonio R. Jiménez
Centre for Automation and Robotics (CAR-CSIC/UPM)
Arganda del Rey, Madrid, Spain
antonio.jimenez@csic.es

***Abstract*—An Attitude and Heading Reference System (AHRS) provides orientation information by fusing sensor data from a magnetic and inertial measurement unit (MIMU). A MIMU consists of three components: gyroscope, accelerometer and magnetometer. A basic AHRS approach fuses two complementary components together using a weighted approach. The first component estimates the relative orientation from the gyroscope, and the second component provides the absolute orientation from the accelerometer and the magnetometer. However, the weighting of these two components is critical to obtain the best orientation information. In order to find the optimal weight a genetic algorithm is used for the optimization task. Results obtained via ground-truth simulated MIMU signals with real noise content reveal that the RMSE orientation error (root means squared error) of the Euler angles in degrees can be reduced by a factor of 3.6 (worst RMSE = 10.054 and best RMSE = 2.764 obtained during a GA run).**

I. Introduction

Orientation information in a three-dimensional space is one of the most important components required for navigation, guidance and control of an object such as an unmanned air vehicle, a drone, etc. An attitude and heading reference system (AHRS) is used to determine the orientation of an object which it is attached to. In the last decade, investigations of attitude estimation have been conducted with low-cost micro electro-mechanical systems (MEMS) [1][2]. Even though MEMS sensors are light weight and small in size and thus applicable to many areas (e.g., human motion tracking), however, they suffer from noise and errors that get accumulated over time. Therefore, the calibration and validation of the AHRS is very important in order to achieve good performance and accuracy.

For an AHRS, sensor data measured by a gyroscope, accelerometer, and magnetometer also known as MIMU (Magnetic and Inertial Measurement Unit) can be used. An AHRS consists of an algorithm which provides the orientation of the sensors with respect to a navigation frame. The orientation is usually represented as Euler angles (roll, pitch and yaw). The aim of an AHRS is to combine the sensor data from the gyroscope, accelerometer and magnetometer to obtain the orientation. An AHRS is conceptually divided into two blocks in order to provide the orientation: (1) from the gyroscope, and (2) from the accelerometer and magnetometer. These two blocks need to be weighted in order to retrieve the optimal orientation information.

This paper uses a genetic algorithm as the optimization method in order to identify the optimal weight of the two blocks of the AHRS. Simulation experiments are conducted to find the optimal weight value such that the error of the AHRS is minimized.

II. Evaluation

In this section, the optimization task is described followed by an introduction of the optimization approach (genetic algorithm), afterwards the sensor data description used for the experiments is given, and then the results of the simulation experiments are provided and discussed.

A. Optimization Task

The basic AHRS approach is described in details by Muñoz et al. [3]. It consists of two components that are fused together as a weighted approach. The first part estimates the relative orientation obtained by integrating the gyroscope angular rate reading from an initial orientation:

$$q_g(k)^- = q_g(k-1)^+ \otimes \delta q(k) \tag{1}$$

where $q_g(k)^-$ is the quaternion orientation given by direct gyroscopic integration at sample time k, and $q_g(k-1)^+$ represents a previous initial or fused estimation. The term $\delta q(k)$ is the micro rotation given at the k^{th} sample interval measured by the 3-axis gyroscope's angular rate w in radians per second. The term δq is computed as:

$$\delta q = [\cos(\frac{|w|dt}{2}), \sin(\frac{|w|dt}{2})\frac{w(1)}{|w|}, ..., \sin(\frac{|w|dt}{2})\frac{w(3)}{|w|}] \tag{2}$$

where $|w|$ is the norm of the gyroscope readings, and $w(1)$, $w(2)$ and $w(3)$ are the three angular rates measured at time k.

The second component provides the absolute orientation from the accelerometer and the magnetometer ($q_{a/m}(k)$). As the gravity vector is known in magnitude and orientation, it is used to derive the absolute pitch and roll of the MIMU. The other euler angle (yaw) is deduced from the known Earth magnetic vector, by projecting the magnetometer readings on a leveled plane and using an electronic compass algorithm. These absolute pitch, roll and yaw angles ($q_{a/m}(k)$) are noisy and subject to many interferences (sudden movements and magnetic perturbations) but do not drift with time being error bounded.

Both components $(q_g(k))^-$ and $q_{a/m}(k)$) provide independent but complementary orientation estimates and thus are fused together ($q_g(k)^+$) in order to benefit from each source of information as shown in Equation 3.

$$q_g(k)^+ = \gamma q_g(k)^- + (1 - \gamma) q_{a/m}(k) \tag{3}$$

This expression includes the fusion of the gyro-based estimation with the absolute accelerometer/magnetometer drift-free correction by means of a time integration constant that is included in the γ term. Thus, the γ value provides the weighting between the gyroscope and the accelerometer/magnetometer portions. In order to identify the γ value that results in the smallest RMSE of the Euler angles, an optimization algorithm is used.

B. Optimization Approach: Genetic Algorithm

The optimization method referred to as genetic algorithm is part of a group called evolutionary algorithms. Evolutionary algorithms are inspired by natural phenomena of biological evolution whereby the common idea is that given a population of individuals, natural selection (biologically referred to as survival of the fittest) is used to improve the fitness of the overall population. For example, given a function to be maximized, a set of candidate solutions is randomly created and a fitness function is used as a fitness measure (the higher the better) is applied. Based on this fitness measure, some of the better candidates are chosen to undergo recombination and mutation (recombination is applied to two candidates and results in two new candidates, whereas mutation is only applied to one candidate and results in one new candidate). After recombination and mutation are applied, the newly created candidates replace the old ones and the next generation begins. This process repeats until a candidate with sufficient quality is determined or a predefined number of iterations is reached [4].

Figure 1 shows the overview diagram of the proposed GA-based parameter optimization. First, the problem (γ value) needs to be encoded using a chromosome representation, and a fitness equation needs to be defined (in our case it is the filter calculation Eq. (3)). Afterwards, the selection method needs to be chosen, and the crossover and mutation operations need to be defined. The overall flow of the algorithm is as follows: first, a randomly generated population is initialized, then the fitness of each chromosome (solution) is evaluated, afterwards the selection process is run whereby the roulette wheel selection method was chosen. Then, crossover and mutation operations are applied in order to recombine potential better solutions. The algorithm terminates once the maximum number of iterations has been reached.

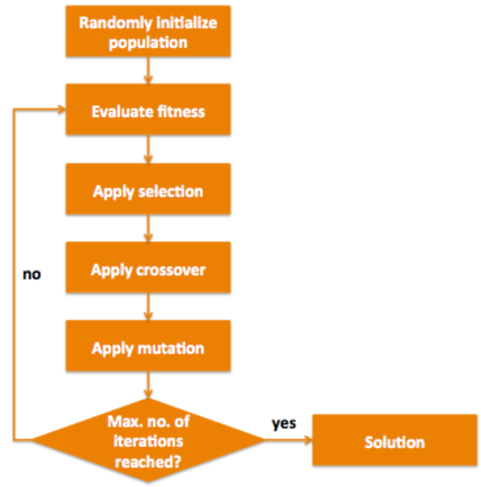

Fig. 1. Flowchart diagram of Genetic Algorithm

C. Data Description

The data used is foot mounted MIMU measurement data [5]. It contains sensor data of a straight trajectory of $1,000$ steps based on a human step pattern characteristics measured by a motion capture system. For our experiments, we have only used partial data of the data set. The information from the MIMU is the acceleration, turn rates from the gyroscope and the magnetic field. The data set includes the orientation (Euler and DCM) ground truth values. The units are in meters, seconds and radians, a sampling frequency of 100 Hz was used, and gravity is $9.8\frac{m}{s^2}$.

As the dataset with orientation ground truth is noiseless, we have added a typical real noise content to the dataset. This noise was generated from a very common MEMS MIMU, XSense MTi unit, by keeping it still during several hours. So different noise windows can be used in order to get different bias conditions and instabilities. The noise patterns have the following features:

- Accelerometer: $0.012\frac{m}{s^2}$ standard deviation random noise and a random constant with a Gaussian distribution and a standard deviation of $0.04\frac{m}{s^2}$ for the bias.
- Gyroscope: $0.0087\frac{rad}{s}$ standard deviation random noise and a random constant with a Gaussian distribution and a standard deviation of $0.015\frac{rad}{s}$ for the bias.

XSense MIMU are commonly used in motion sensing applications, and are seen as the gold standard for scientific research [6]-[9].

Figure 2 shows the sensor data obtained by the gyroscope, accelerometer, and magnetometer. The cyclic steps of the walking motion can be observed.

D. Simulation Experiments

Different configurations of the GA were run, but the one that resulted in the best run is reported below:

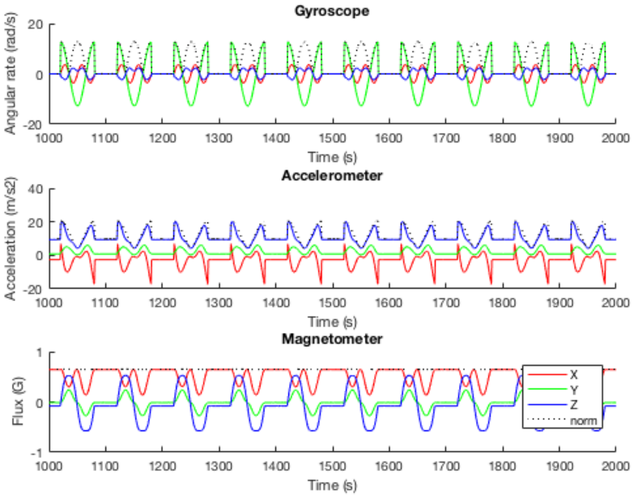

Fig. 2. Sensor data of gyroscope, accelerometer, magnetometer

- Size of a chromosome population = 30
- Number of genes in a chromosome = 8
- Crossover probability = 0.8
- Mutation Probability = 0.001
- Number of iterations = 30

Figure 3 shows the performance plot of the genetic algorithm optimization. As can be seen, the average fitness (RMSE) of the population is 9 initially reducing to 3.1 after 30 iterations. The best chromosome has a fitness value of 2.7646 which refers to a γ value of 9.843137e-01. The worst chromosome returned an RMSE value of 10.0547.

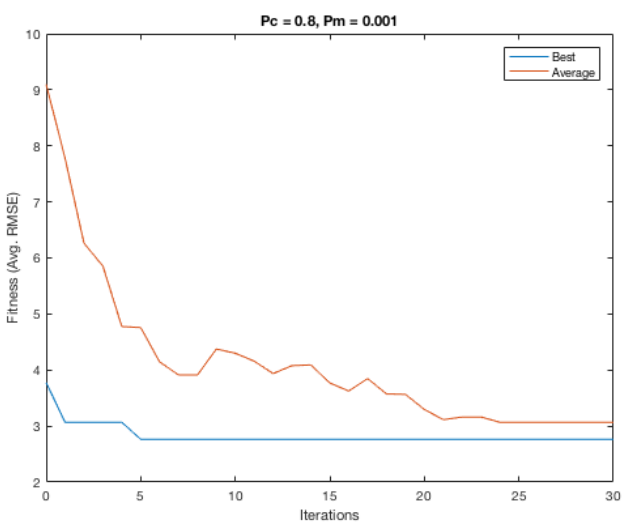

Fig. 3. Performance plot of Genetic algorithm optimization

Using the best γ value of 9.843137e-01 resulted in the following Euler estimation correctness as shown in Figure 4. Very close values are achieved in terms of roll, pitch, and yaw.

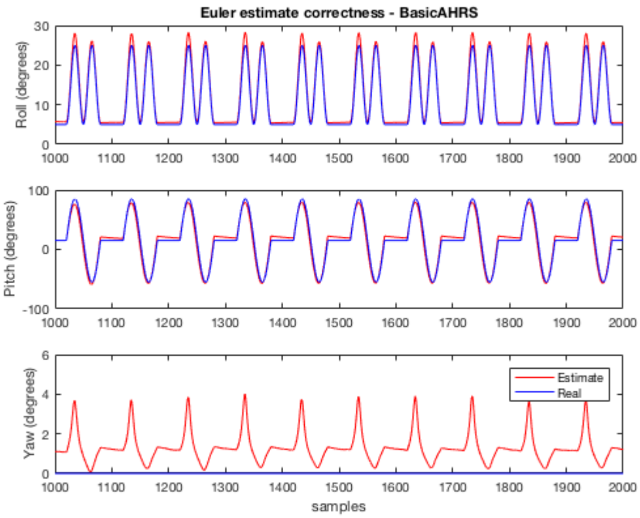

Fig. 4. Euler estimation correctness of Basic AHRS

III. Conclusion

A basic AHRS approach fuses two components together using a weighted approach. The first component estimates the orientation from the gyroscope, and the second component provides the orientation from the accelerometer and the magnetometer. However, the weighting of these two components is critical to obtain the best orientation information. In order to find the optimal weight a genetic algorithm is used for the optimization task. Therefore, simulations were run in order to optimize and identify the best weight value. The results show the RMSE (root means squared error) of the Euler angles and the best value obtained was an RMSE of 2.7646 whereas the worst RMSE was 10.0547. Thus, a reduction of the error of 3.6 was achieved using the genetic algorithm optimization method.

As for future work, further optimization runs will also include other threshold values, such as the threshold for rejecting the $q_{a/m}$ estimations when the magnitude of acceleration is significantly higher or lower than the gravity (a symptom that the user is moving abruptly, and so the attitude information from the accelerometer/magnetometer becomes unreliable).

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