Review, classification, and evaluation of algorithms for orientation estimation

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1 Introduction

Determining object orientation (attitude and heading) is an important problem, especially in the fields of aerospace, medicine robotics and drones. A large number of sensors can be used to determine the orientation of a rigid body relative to a reference (usually navigation) frame. For example, GNSS, visual sensors, LiDAR and especially inertial measurement unit and magnetic sensor. This paper will discuss the use of inertial sensors, namely of gyroscope, accelerometer and magnetometer to determine orientation, since the use of a combination of some or all of these sensors is commonly used approach. Moreover, the inertial sensors are an affordable solution that is not as susceptible to jamming as GNSS. Advances in the development of cheap and accurate MEMS sensors and demand for orientation estimation in various applications has led to the development of various algorithms for fusing information from these sensors. These algorithms will be hereafter referred to as attitude and heading reference systems - abbreviated as AHRS.

2 Classification of AHRS techniques

A plethora of papers dealing with various AHRS techniques have been published so far. In addition to the precision and robustness of the estimation, these techniques also differ in terms of their implementation requirements - in the number of tunable parameters and in how important and intuitive it is to set them correctly. It is not possible to claim that any one of these techniques is the best one. The selection of the AHRS for the most accurate estimation under expected conditions may conflict with the requirement for reliability under adverse conditions, and both of these requirements may often conflict with the requirement for computational efficiency. In general, these techniques can be divided into several categories:

AHRS based on Strap-down integration (SDI) is based on idea that gyroscope provides measurements of the angular velocity thus allowing the *relative* orientation determination based on the known initial orientation by integrating the gyroscope output. Integrating gyroscope outputs leads to a gradual accumulation of error - the rate of this accumulation depends on the quality of the gyroscope used.

Vector Observations (VO) AHRS works on the idea that if the value of two or more vectors in a navigation frame is known and their measurement in a body frame is available, then the orientation can be determined. Thus, it is possible to make a *absolute* attitude and heading estimation based on the measurements of gravity and magnetic field vectors. These algorithms are usually computationally inexpensive, but the quality of their estimation is limited by the fact that the accelerometer is susceptible to external non-gravitational acceleration and

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the magnetometer is susceptible to magnetic field distortion.

The following AHRS categories are based on the fact that the gyroscope and accelerometer with magnetometer provide measurements with complementary error properties. Fusion of those measurements by AHRS leads to long term reliable and precise orientation estimation.

AHRS based on Complementary filter (CF) is based on the idea of using filtering in the frequency domain. The gyroscope output is filtered by a high pass filter and the orientation estimation using the accelerometer and magnetometer measurements is filtered by a low pass filter. The resulting estimates of orientation are then merged.

AHRS based on the Kalman filter (KF) Gyroscope is usually used during the time update to predict the current orientation and accelerometer and magnetometer are used during the measurement update to correct this prediction. The advantage of this approach is that KF provides a covariance matrix. The disadvantage of KF based AHRS is that it requires a mathematical model, unlike CF based AHRS.

AHRS based on neural networks (NN) is a dynamically developing method of orientation estimation in recent years. Neural networks process measured data without an explicitly defined model or directly provided knowledge of the meaning of the processed data. Despite this, they are able to learn from training data the relation between sensor measurements sought and orientation.

3 Experiment

At least one representative of each approach was selected and implemented to compare the different AHRS techniques. In particular, the following were compared: Attitude from angular rate (abbreviated as Afar), Super-fast Attitude from Accelerometer and Magnetometer (abbreviated as SAAM), Madgwick filter, VQF, ahrsfilter based on KF (abbreviated as matlabKF), RIANN. RIANN does not utilise magnetometer measurements, therefore it does not provide reasonable estimate of the yaw angle. For all of them, the tunable parameters were set to give the best possible orientation estimation. The merged dataset used in the (Justa et al. , 2020) paper was used for the comparison. The results of this comparison are shown in Table 1. From the results of the experiment, it can be concluded that none of the groups of AHRS techniques based on fusion of gyroscope with accelerometer and in the case that the heading is determined with magnetometer (KF, CF, NN) achieves with well chosen tunable constants clearly better results and therefore none of these groups is clearly better than the others. VO AHRS and SDI AHRS achieved worse results in the experiment, which is consistent with the expected behaviour. The estimates provided by VO AHRS were particularly poor in the third part of the experiment, in which the platform was subjected to dynamic acceleration.

Used filter	type of filter	RMSE of roll [deg]	RMSE of pitch [deg]	RMSE of yaw [deg]
Afar	SDI	15.424	6.698	13.999
SAAM	VO	16.725	7.234	23.431
Madgwick	CF	5.492	3.033	7.021
VQF	CF	5.839	2.670	6.909
matlabKF	KF	5.947	2.571	6.600
RIANN	NN	6.003	2.604	-

Table 1: Results of the Experiment

References

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Justa, J., Šmídl, V., and Hamáček, A. (2020). Fast AHRS filter for accelerometer, magnetometer, and gyroscope combination with separated sensor corrections. *Sensors*, 2020; 20(14):3824.