Orientation tracking by Inertial Sensing-A Review

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Abstract—this paper is a review of the research done in the use of inertial sensors for tracking the orientation of subjects. It provides an overview of the sensors involved (gyroscope, accelerometer, magnetometer) and their limitations. Methods for sensor fusion involving Kalman and complementary filters have been reviewed. Several techniques for specifying orientation -Euler angles and quaternions are also discussed.
Keywords: *gyroscope, Kalman, orientation, quaternion, tracking.*

1. Introduction

An Inertial Measurement Unit (IMU) is a combination of inertial sensors, such as accelerometer, magnetometer and gyroscope. It is a main component in inertial navigation systems where it is used to obtain the device's velocity, orientation and the gravitational force acting on it.

Orientation tracking has found extensive use in mobile games, virtual reality as well as activity recognition of the user carrying the device. This may, for instance, help in adjusting the display of the device according to the orientation of the mobile device with respect to the user.

This paper presents a review of the research done in using inertial sensors for real-time orientation tracking of subjects in a 3-D space. But the readings thus obtained are prone to errors which prevents their efficient use. Hence, these errors must be accounted for. Methods for the same have been explored by many researchers, and their findings have been summarized here.
Selection of the sensors to be used is another issue, which is concerned with not only the capabilities of the sensors, but also their shortcomings as well as the algorithm used. Another consideration is the selection of method of transformation of results from one coordinate system to another. For this, rotation matrices, Euler angles and quaternions are used with quaternions being the most popular choice because of their mathematical elegance

The paper concludes by presenting the results, as found in these researches, showing how the use of Kalman filter for sensor fusion can increase the efficiency of the system.

2. Inertial Sensors

Accelerometer: It is a device that measures the acceleration along its axes. A tri-axial accelerometer can be used to obtain not just the net acceleration, but also its direction.
Gyroscope: It is a sensor that measures the components of angular velocity, about its axes. It can be used to continuously read the difference between the current orientation and the previous one.
Magnetometer: It is a device for measuring the magnitude and direction of the magnetic field acting on the device.

3. Orientation and Gravity Components

3.1. Initial Orientation

Orientation can be defined as a set of parameters that relates the angular position of a frame to another reference frame. Paper [1] proposed a method to obtain orientation using both the accelerometer and gyroscope sensors. The gravitational component, obtained from accelerometer, was used to make an estimation of the tilt - the angle between the sensor axes and the vertical. This tilt estimation does not suffer from integration drift.

The sensor orientation calculated with gyroscopes was split into a tilt part and an angle, representing a rotation around the vertical. This tilt from the gyroscopes was fused with the tilt from the accelerometers with a Kalman filter, thus showing diminished error as compared to orientation error obtained by solely integrating angular velocities from gyroscope which introduced integration drift in the estimate.

A method to estimate the constant gravity vector [1] was proposed in paper [2]. By averaging the accelerometer readings on all the three axes in a chosen sampling interval, the components of the gravity vector were obtained. These were then, by means of vector algebra, used to estimate the vertical component of the acceleration caused by user's motion and then magnitude of the horizontal component of the same, independently of how the three-axis accelerometer system is oriented.

Paper [3] showed how the sensor readings from an accelerometer and a magnetometer could be used to get accurate measurements of the yaw, pitch and roll of the device in a steady state. In the steady state, the only force acting on the device is gravity, whose magnitude is predetermined, and direction is vertically downwards. Hence, it can be used to get the orientation of the device with the vertical axis, using the accelerometer readings. Also, considering the earth's magnetic field to be the only one acting on the device, the orientation of the device with this axis can also be found, using the magnetometer readings. Thus, the net orientation of the device with the earth's frame of reference can be obtained. These values are periodically compared with the orientation obtained by integrating the angular velocity obtained using two gyroscope in the IMU, to adjust the parameters for an adaptive filter for the sensors.

3.2. Keeping Track of Orientation

There are numerous methods for describing this relation. Some are easier to visualize than others are. Each has some kind of limitations. Among them, rotation matrices, Euler angles and quaternions are commonly used. Advantages and disadvantages of each of these methods are available in [10] along with a thorough discussion of each.

Euler angles, sometimes referred to as orientation angles, are a compact method of specifying orientation which is commonly used in a number of different fields. This specification consists of the rotation angles around three independent axes which are required to achieve a desired orientation. Unfortunately, the choice of axes about which these rotations are performed is somewhat arbitrary resulting in as many as 24 different possibilities. Most common Euler angles are yaw, pitch and roll of the airplane. As stated by [10], they are easy to understand and hence most popular. But a serious limitation, as mentioned in [10], is the singularities suffered by certain sets of Euler angles. A case often referred as gimbal lock was mentioned in [11] when the pitch and yaw axis of rotation become aligned so that they are no longer independent resulting in a loss of degree of freedom about the yaw axis and the body effectively rotates in a degenerate two dimensional space.

Quaternions are an alternate method of orientation representation ideally, one would like a representation which explicitly contains the geometric information of axis and angle of rotation in a numerically well-conditioned manner along with a straightforward method of combining successive rotations. Such a representation is possible through the use of quaternions, a mathematical entity composed of a scalar and vector pair denoted here as (s,v). The axis and angle of rotation required to achieve an orientation can be represented by the unit quaternion $(\cos(\theta/2);\ k \sin(\theta/2))$ where the magnitude of quaternions is defined as

$$|(\mathbf{s},\mathbf{v})|^2=\mathbf{s}^2+\mathbf{v}.\mathbf{v}$$

Quaternion rotation is more efficient than the use of transformation matrices and does not involve the use of trigonometric functions [10].The optimizations achieved with quaternion are mentioned in [10] along with an important constraint that the norm of quaternion must be unity. This is difficult to achieve but various techniques have been proposed. Here, norm is defined as square root of a determinant of matrix corresponding to a quaternion, i.e., the square root of a product with its conjugate, as with complex numbers. [10] also shows that quaternion representation is well-suited to integrate the angular velocity of a body over time. It further explores rotation matrix as an alternative to Euler angles and quaternion both, as it does not suffer from singularities and has no unit norm constraint. It is not, however, without its disadvantages. One such disadvantage is the high degree of redundancy implicit in this representation. Since orientation can be shown to possess only three independent degrees of freedom, it can be represented by three variables. The extra six elements in the rotation matrix [10] are a result of the orthonormality constraint, three of which are required to maintain unit length of the columns (rows) and three to maintain the orthogonality of the columns (rows.) This results not only in extra data storage but also creates difficulties when interpolating between two orientations. In addition, the rotation matrix specification of orientation does not explicitly represent the axis or angle of rotation required to achieve the given orientation. This axis and angle are implicitly included in the matrix and must be computed separately.

4. Limitation of Sensors

Gyroscope: Although gyros can provide a high level of accuracy in determining angular changes, it comes at the cost of high power consumption. As [4] mentions, on an average, a gyroscope can consume 5 to 10 times more power, as compared to the combined total for an accelerometer and a magnetometer. Hence, [4] tries to avoid its use completely.

Magnetometer: The magnetometer suffers from huge amounts of error, mainly due to the effects of proximity to magnetic materials, such as iron, which is indispensible in today's world. Hence, it is rendered useless, especially indoors.

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5. Errors in Sensors and Their Removal

5.1. Causes of Errors

Life would have been perfect had these sensors been error-free. But unfortunately, they are not. Errors are introduced due to the following reasons in general [3].

1. Scale factor (ratio of the change in the output to the change of the input intended to be measured)
2. Bias (average output of the sensor over a time measured at specified operating conditions that has no correlation with the input)
3. Inefficient construction (results in nonlinearity of the

relationship between tilt angles and output voltages)
4. Presence of ferrous objects in the vicinity (results in huge deviations in magnetometer readings)

5.2. Removal of Errors

A complete list of the different errors associated with each of these sensors has been given in [10].Several papers have focused on how to reduce these errors. Procedures for estimating these errors, based on the root causes of the errors, as mentioned above, and using simple mathematical formulae, have been given in [3]. Also, if the errors of the sensors can be limited to a certain maximum, certain voltage thresholds can be set to detect whether the device is at rest or in motion.

Paper[4] suggested that a linear adaptive filter could be created using the readings from just a magnetometer and an accelerometer. Using the Kalman filter so created for fusion of data from the sensors can help improve the efficiency of orientation measurement considerably.

The use of an average window before application of the filter is also advocated. An alternative to Kalman filter, a complementary filter, was presented in paper[6]. These two filters have been explained in the next sub-section.

5.3. Kalman Filter

The bias is major source of error in IMUs with low cost sensors. Paper [5] therefore investigated Kalman filtering for orientation tracking. Various capabilities of Kalman filter, as mentioned in [5], made it a suitable choice for estimating rotation angle.
The gyroscope signal, known to suffer from drift during long term, made it unsuitable for obtaining absolute orientation of the system concerned. The Kalman filter, which used measurement signal from gyroscope and a separate information signal from a magnetic sensor, was shown [7] to provide a better estimate of the absolute orientation over long duration, after comparison with a reference potentiometer signal.However, proper pecautions were taken during the experiment so that interference due to external sources of magnetic field was minimum.

5.4. Complementary Filter

Paper[6] reviewed complementary filtering and showed its relationship to Kalman filtering. It showed the application of complementary filter approach to an inertial system where a basic complementary filter was used to estimate position and velocity. The filter was obtained by a simple analysis in the frequency domain and did not consider noise corrupting the actual signals .Also, a kalman filter was developed for the same problem in time domain which relied on noise corrupting the signals instead of actual signals to be estimated, unlike the complementary filter. But this involved more computation as compared to complementary filter approach.

Paper[7] thus proposed an improved version of kalman filter which was used for tracking orientation of human body. MARG (Magnetic, Angular Rate and Gravity) sensors were used for real-time orientation tracking. The traditional equations of Kalman filter were not used as it is because of the nonlinearity relationship between output equation of this filter and the state vector. Thus, a Gauss-Newton method was applied to each pair of accelerometer and magnetometer readings and a quaternion was obtained which formed the measurement for the kalman filter whereas the angular rate measurements were available from angular rate sensors. Thus, three angular rate measurements followed by four quaternion components formed the entire measurement vector for the kalman filter. The state vector was also similarly 7-dimensional.The state and measurement equations were derived accordingly in discrete form and standard Kalman filter equations were then applied for computer implementation. The output equation of Kalman filter was linear and the design of Kalman filter was greatly simplified.

6. Results

In [5], ten different measurements were considered at nine different measuring times. The average of difference between gyroscope and kalman estimates after each measurement was taken for each measurement time. The corresponding improvement, in percentage, is shown in Table 1.

Table 1: Improvement of the Kalman filter for several measurement times

Measurement time (s)	The median improvement for ten measurements (%)
20	70
40	80
60	82
80	90
100	92
120	94
140	94
160	95
180	98

This is also evident from Fig. 1 below, from which it was observed that the kalman does not follow the gyroscope signals which suffer significant drift as the divergence ($\Delta\varphi$) of the same is 322° after 120s which is less than 5° for kalman from the indicated reference signal

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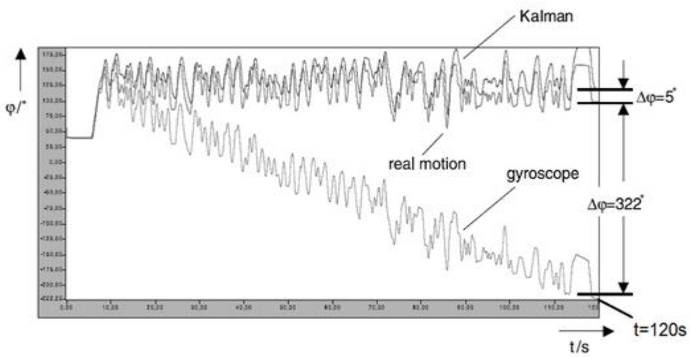

Fig 1: recorded angles for a period of 120 seconds

Also, paper[1] showed considerably diminished orientation error by fusion of accelerometer and gyroscope data using Kalman filter which is evident from Fig. 2.The error was defined by the amount by which calculated orientation must rotate to meet the original orientation.

Thus, significant improvements in orientation tracking were observed with kalman filter.

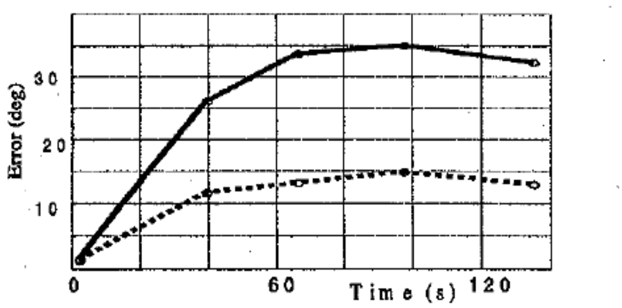

Fig 2:Example of calculated orientation error from [1] by integration of gyroscope signal (solid) and by kalman filtering of gyroscope/accelerometer signal(dashed).

7. Conclusion

Considering the limitations of magnetometer [3], especially indoors, gyroscope seems a better choice for tracking orientation. Fusion of gyroscope data can be done preferably with accelerometer, instead of magnetometer, data by a Kalman filter.
The use of Kalman filter is well established for this purpose and several methods have been proposed by researchers to reduce the computational costs of the same.
Quaternions are preferred choice for specifying orientation due to their simplicity and mathematical elegance as compared to rotation matrices which are computationally intensive and Euler angles which suffer from singularities.

8. Future Scope

If the redundancy in using rotation matrices could be reduced, or if the norm constraint for quaternions could be accounted for efficiently, it may be possible to improve upon the cost of calculations involved.
Also, if better filters could be designed, or if the quality of the sensors manufactured could be improved, the accuracy of system could be improved as well.
The papers reviewed here focused only on finding the orientation of the device using the IMU. Currently, research is being carried on for the use of these sensors for tracking the location or path of the subjects as well. This may be achieved by using the accelerometer for finding the acceleration in the earth's frame of reference, and integrating that twice to find the distance travelled, while a gyroscope may be used to keep track of the orientation.

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