Accuracy Analysis of IMU Navigation Algorithms

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Abstract. During the last few years microminiaturized inertial sensors were introduced in many applications. Their small size, low power consumption, rugged construction open doors to many areas of implementation. Many algorithms were advertised to process inertial measurements. Usually the developers of new smart sensor applications have to make a compromise between algorithm complexity, sensor quality and energy saving strategy. In this paper the accuracy of several navigation algorithms is discussed. Two main cases are regarded: using real sensor data and simulated ones. For the first case the most important accuracy indicator is how fast the error in sensor attitude and sensor position is accumulated. For the second case mean square error of estimated parameters is used. The received results are useful for suitable choice of the lowest complexity navigation algorithm with a sufficient for given application accuracy. Something more, the paper gives an idea how to estimate or orientate in applicability of existing big variety of algorithms without complex and very expensive test devices.

Keywords: Inertial Measurement Unit, Navigation

1 Introduction

Inertial Measurement Unit (IMU) consists from one or more sensors, measuring the change of kinematic energy of a moving body. The sensors are divided in two groups: gyro sensors and accelerometers. Gyro sensor measures rotation rate of the body. Accelerometer provides information about linear acceleration of the body. Usually description of 3D motion of a body is given by 3 orthogonally placed accelerometers giving transition dynamic of the body and 3 orthogonally placed gyro sensors determining the orientation/attitude of the body. The axes of the both types of sensors normally coincide – e.g. in a 3D orthogonal coordinate system there are sensors to measure linear accelerations on each of the axes and rotation rate of the same axes. Thus the calculation process is also simplified. Two type of IMU were realized in the years. The first one is built on the scheme of the classical gyroscope and it preserves one and the same (initial) position, remaining independent of body rotation. In this case the body orientation is measured as a difference between gyroscopes axes orientation and the present orientation of the body - its roll, pitch and yaw. The second one, called also strapdown gyro sensor, is fixed tightly on the body and provides measurement of rate of rotation of the body. For this class of sensors, the body orientation is received

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through the integration of gyro measurements in respect to a priori known body orientation. Usually the strapdown sensors are produced as a MEM device with extremely high robustness and low power consumption. In this paper such a type of devices will be considered. The Inertial Navigation System (INS) is a system that relies entirely on inertial measurements for determination of dynamical body position and orientation. Today a wide range of strapdown INS is available on the market.

In this paper several INS algorithms were examined in order to estimate their accuracy and complexity. Two scenarios were regarded. The first one uses real sensors data and the second is based on simulated data. The computer generated data emulates inertial sensor measurements in accordance with the precision and accuracy specifications of particular sensor sample.

The paper is organized as follows. In the next chapter the chosen method of accuracy estimation is justified. Then the mathematical background for INS algorithms is described. The fourth chapter gives the results from experiments. The concluding remarks are given the last chapter.

2 Algorithm and sensor accuracy estimation

3 IMU based navigation

3.1 Theoretical background

The body motion in an inertial frame of reference can be described as a result of simultaneous action of two forces - gravitational F_g and specific F_{sp} :

$$a_i = \frac{F_{sp}}{m_b} - \frac{F_g}{m_b} = a_{sp} - g \tag{1}$$

where g is acceleration, caused by gravitational force and a_{sp} is the acceleration caused by specific force. Gravitational force is a function, depending on the distance between body and the Earth:

$$F_g = G\frac{M_e m_b}{r^2} \tag{2}$$

where G is the gravitational constant $G = 6.6742*10^{-11}$, r is the distance between the interacting bodies, M_e is the mass of the Earth and $K = GM_e = 398600.44*10^9$.

To explain the specific force we introduce three frames of reference - one assosiated with the moving body, denoted by subscript $_b$, the second one is a geocentric frame, rotating with the rate of rotation of the Earth - it is associated with the subscribt $_e$ and the last one is also geocetric, but it is inertial and it is marked by subscribt $_i$. Let now denote the rate of the Earth rotation by ω. The last introduction note concerns the differential of a vector in absolute reference frame if it is presented in rotating system:

$$\frac{de_a}{dt} = \frac{de_r}{dt} + \omega \times e_a \tag{3}$$

Let now express the velocity in inertial reference frame, applying expression from (3):

$$v_i = \frac{dr_e}{dt} + \omega \times r_e = v_e + \omega \times r_e \tag{4}$$

The next step is to express acceleration, applying twice (3):

$$a_i = a_e + 2\omega \times v_e + \omega \times \omega \times r_e - g \tag{5}$$

The acceleration $2\omega \times v_e$ is result of Coriolis force, and the term $\omega \times \omega \times r_e$ corresponds to centrifugal acceleration. Usually the last two terms of (5) are grouped together and replaced by so called local gravitational acceleration or simply gravity:

$$a_i = a_e + 2\omega \times v_e - g_l(h) \tag{6}$$

where h is the height of the body above the Earth surface. The equation (8) is regarded as fundamental navigational equation.

It is worth to estimate the significance of all terms. Let consider a motion with velocity of 36 km/h on the Earth surface near to Equator. The applied force creates acceleration equal to 1 m/s^2. For this example $a_e = 0.1g$, $2\omega \times v_e = 1.46 * 10^{-3}$, $\omega \times \omega \times r_e = 3.4 * 10^{-2}$.

For calculation of g_l the Gelmert formula is applied:

$$g_l(h) = 9.7803(1 + 0.005302 \sin^2 \varphi - 0.000007 \sin^2 2\varphi) - 0.00014 - 2\omega_0^2 h$$

3.2 Naive integration technique

3.3 Simplified navigation algorithm

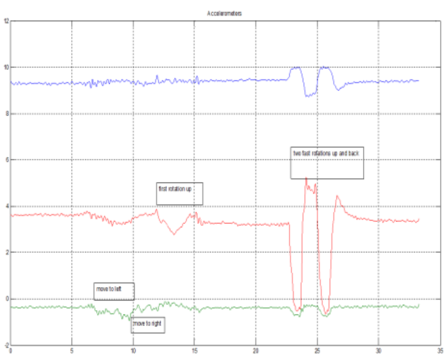
3.4 Navigation by solving differential equations

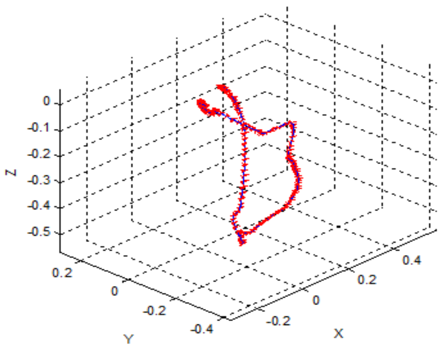
3.5 How to avoid critical rotations near 90^0

3.6 How to diminish accelerometer bias trend

4 Experimental results

4.1 Real sensor data





4.2 Simulated data

5 Conclusion

In this paper four contemporary algorithms for strapdown INS are examined on real and synthetic data. The comparison analysis allows developers to chose the most suitable of them optimizing given criterion. The proposed approach gives a feeling of sensors and algorithm inaccuracy without expensive test equipment.

Acknowledgement:

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