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# Development of Wireless Gyroscope-free Inertial Measurement Unit

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## ABSTRACT

This paper aims to develop a wireless gyroscope-free inertial measurement unit (GF-IMU) in order to directly measure the transversal acceleration as well as the angular acceleration and angular velocity of target structure. The sensor board only contains four 3-axial accelerometers. Multiple distributed orthogonal triads of accelerometers that consist of three non-planar distributed triads equally spaced from a central triad as a specific configuration is developed. Twelve channels of analog acceleration data is collected and transferred to digital signal using a customized data acquisition board, and then wirelessly transmitted to gateway node using iMote2 board. The iMote2 module follow IEEE 802.15.4 communication protocol. As using accelerations sensors it is not possible to determine the direction of rotation. To overcome this drawback, a weighted average coefficient is applied to fuse the information of angular acceleration and the angular velocity and thus robustly estimate the direction of rotation. The GF-IMU system is evaluated by ABB IRB140 6DOF robotic arm. This design achieves much lower power consumption, smaller dimension and lower cost than traditional inertial sensor systems. It shows great potential in analysing the translation and rotation of certain structure for the purpose of structure health monitoring (SHM) applications.

**KEYWORDS:** *SHM, gyroscope-free inertial measurement unit, iMote2, weighted average coefficient*

## 1. INTRODUCTION

An inertial measurement unit (IMU) [1] is a unit that be used to measure the relative movement of body. It has been developed for decades to provide continuous, non-invasive motion/gesture capture for a variety of applications, including body state estimation, microsurgery, fall detection and rehabilitation, etc. [2,3] A traditional IMU comprised of 3-axis linear acceleration measurement by accelerometers and 3-axis angular velocity measurement by gyroscopes mounted in a strapdown configuration. As the development of MEMS technology [4], commercial products of MEMS gyroscopes are already available on the market. However they are still afflicted with certain disadvantages like high cost, high power consumption and more inherent physical complexities than MEMS accelerometers. Therefore, there is needs to develop a gyroscope-free inertial measurement unit for applications requiring low cost and moderate performance.

In general, the GF-IMU [5, 6] is required to be capable of deriving linear acceleration, angular acceleration and angular velocity. Because the latter two states have integrative/derivative relation, a GF-IMU comprised of 6-axis measurements is theoretically capable of yielding all three states. Chen [7] firstly proposed a cube-type GF-IMU which has one accelerometer at the center of each surface of a cube. The system was carefully evaluated [8] and improved [9] by adding a 3-axis acceleration measurement. However, due to the quadratic formulation of angular velocity in the rigid body dynamics, the derivation of this state in the 9-axis IMU faces the sign ambiguity problem [10]. This dilemma can be solved by comparing it to the estimated angular velocity which is integrated from the angular acceleration measurement [11]. Parsa [12] later developed an all-accelerometer IMU which requires twelve 1-axis accelerometers mounted at specific locations at the specific location on the surface of a cube. The system is capable of deriving all three states in which the angular velocity was derived through an optimization procedure from six measured inputs in the quadratic form. Edwan [13] continued this work by using four 3-axis accelerometers instead and utilizing dynamic model and extended Kalman Filter (EKF) to yield all three states simultaneously.

This paper aims to demonstrate the potential structure health monitoring applications by using a GF-IMU to measure structure motion (translation and rotation) in 3-dimensional space.

# 2. CONFIGURATION OF DISTRUBUTED 3-AXIS ACCELEROMETERS

## 2.1. Spatial Configuration

A configuration consisting of four 3-axis accelerometers that follows the rules listed by Zappa [11] is adopted. The configuration shown in Figure 2.1 has four rigidly 3-axis accelerometers, symbolized as A, B, C and D. This configuration is used mainly because a minimum of twelve accelerometers are needed to determine the magnitude of the angular velocity and its direction.

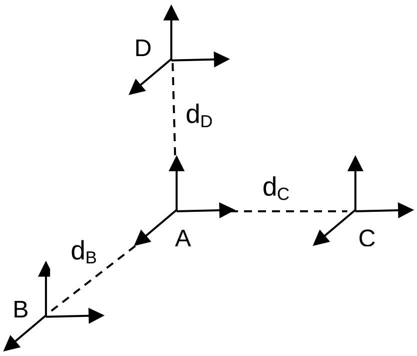


Figure 2.1 Spatial configuration of four 3-axis accelerometers

## 2.2. Measurement Model

This specific configuration was analysed by Algrain [14] where the greatest amount of angular motion information (AIV) composed of nine angular terms shown in Equations [15] (2.1)-(2.9) can be extracted from this configuration.

$$\dot{w}_x = (\mathrm{a}_z^C - \mathrm{a}_z^A)/2d_c + (\mathrm{a}_y^A - \mathrm{a}_y^D)/2d_D \tag{2.1}$$

$$\dot{w}_y = (\mathrm{a}_x^D - \mathrm{a}_x^A)/2d_D + (\mathrm{a}_z^A - \mathrm{a}_z^B)/2d_B \tag{2.2}$$

$$\dot{w}_z = (\mathrm{a}_y^B - \mathrm{a}_y^A)/2d_B + (\mathrm{a}_x^A - \mathrm{a}_x^C)/2d_C \tag{2.3}$$

$$w_x w_y = (\mathrm{a}_y^B - \mathrm{a}_y^A)/2d_B + (\mathrm{a}_x^C - \mathrm{a}_x^A)/2d_C \tag{2.4}$$

$$w_x w_z = (\mathrm{a}_y^B - \mathrm{a}_y^A)/2d_B + (\mathrm{a}_x^D - \mathrm{a}_x^A)/2d_D \tag{2.5}$$

$$w_y w_z = (\mathrm{a}_z^C - \mathrm{a}_z^A)/2d_C + (\mathrm{a}_y^D - \mathrm{a}_y^A)/2d_D \tag{2.6}$$

$$w_x^2 = (\mathrm{a}_x^B - \mathrm{a}_x^A)/2d_B + (\mathrm{a}_y^A - \mathrm{a}_y^C)/2d_C + (\mathrm{a}_z^A - \mathrm{a}_z^D)/2d_D \tag{2.7}$$

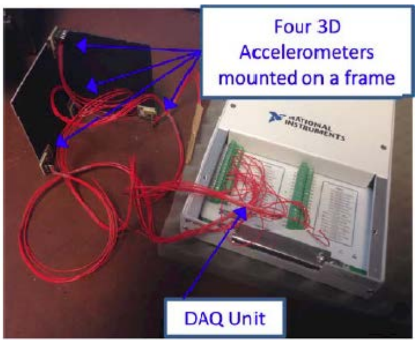
$$w_y^2 = (\mathrm{a}_y^C - \mathrm{a}_y^A)/2d_C + (\mathrm{a}_x^A - \mathrm{a}_x^B)/2d_B + (\mathrm{a}_z^A - \mathrm{a}_z^D)/2d_D \tag{2.8}$$

$$w_z^2 = (\mathrm{a}_z^D - \mathrm{a}_z^A)/2d_D + (\mathrm{a}_x^A - \mathrm{a}_x^B)/2d_B + (\mathrm{a}_y^A - \mathrm{a}_y^C)/2d_C \tag{2.9}$$

The notation

$$w_{i,j} = w_{i,j-1} + \Delta t\left(\frac{\dot{w}_{i,j-1} + \dot{w}_{i,j}}{2}\right), \quad i = x, y, z \tag{2.10}$$

Where the subscripts



platform with a customized DAQ board collecting the 12 channel acceleration data as shown is Figure 3.2. The Imote2 provides an advanced sensor node platform aimed specifically at applications with intensive computational requirements. An integrated low-power 802.15.4 radio transceiver (ChipCon CC2420) supports a 250kb/s data rate with a transmission range of up to 100 m.

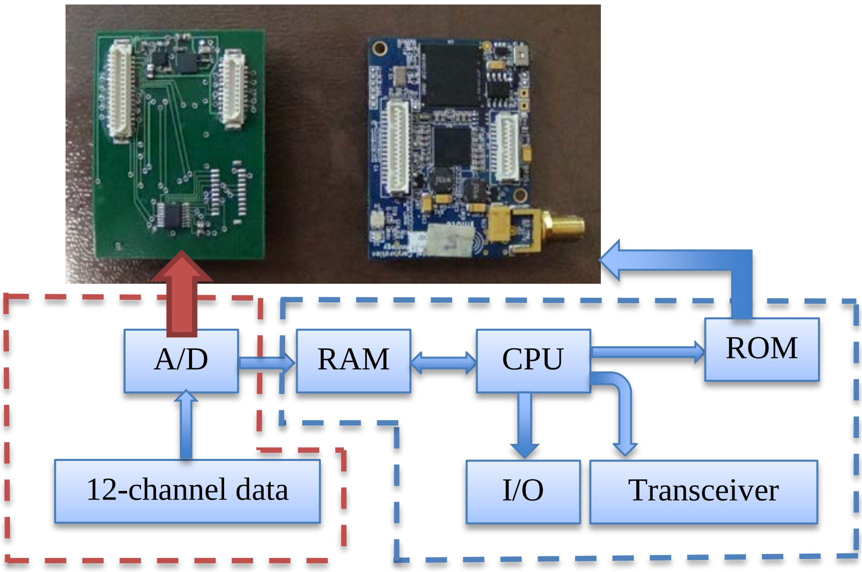


Figure 3.2 Hardware schematic of the sensor node

The DAQ board includes a 12-channel A/D converter (MAX1239), a voltage regulator (LP2989AILDX-3.3) and I/O ports to iMote2 and accelerometers. Sampling at 200 kHz, the ADC communicated with the iMote2 through the Serial Peripheral Interface (SPI).

## 4. EXPERIMENT RESULTS

### 4.1. Calibration

In the general case, orientation of the sensing axes of the 3-axis are unknown. Assuming a known acceleration vector

The calibration process is completed by making use of gravitational acceleration in six measurements [19]. Table I shows the relation between orientation of the accelerometer and its output.

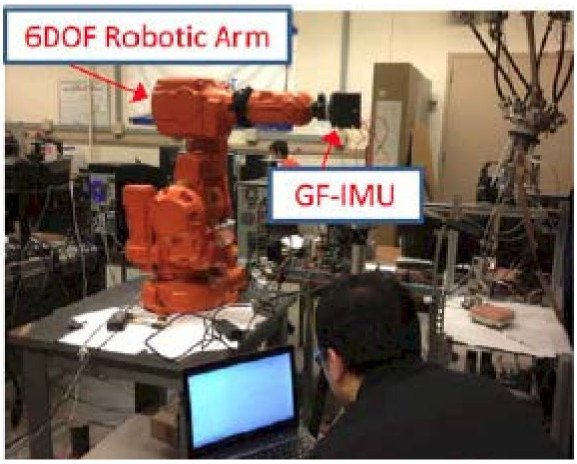
Table 3.1. Relation between orientation of accelerometer and its output

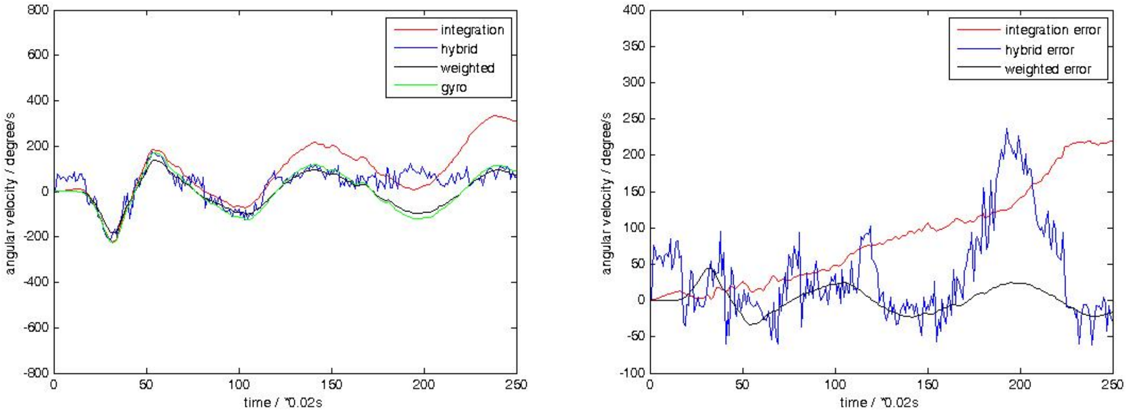
| Stationary position | Accelerometer | | |
|---|---|---|---|
| | $A_x$ | $A_y$ | $A_z$ |
| Z down | 0 | 0 | +1 g |
| Z up | 0 | 0 | -1 g |
| Y down | 0 | +1 g | 0 |
| Y up | 0 | -1 g | 0 |
| X down | +1 g | 0 | 0 |
| X up | -1 g | 0 | 0 |

Therefore, the problem can be solved in least squares method as

$$\theta = (H^T H)^{-1} H^T z \tag{3.4}$$

And the sensitivity matrix





(a) (b)

Figure 3.4 (a) Angular velocity estimated by GF-IMU data processed with three different methods (integration, hybrid and weighted) compared to the results of gyroscope measurement in the x-axis
(b) Angular velocity estimation error by 3 methods compared with that by the gyroscope

## 5. CONCLUSION

In this paper, a wireless GF-IMU system is developed based on distributed accelerometers to derive angular information vector. Three different algorithms were developed to estimate angular velocity from the signal acquired by the four 3-axis accelerometers. Experiment result shows that weighted average method has better performance than integration method or the hybrid method in achieving smallest error in the angular velocity measurement.

The potential applications of the GF-IMU system based on the design principle, upon further refinement, include to measure the structure health conditions.

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