REAL-TIME WIRELESS SENSING
WITH SPATIOTEMPORAL TRACKING

Matthew J. Whelan and Kerop D. Janoyan
Clarkson University, Department of Civil and Environmental Engineering
8 Clarkson Ave, Box 5710, Potsdam, NY 13699
Phone: (315) 268-6506, Fax: (315) 268-7985, email {whelanmj, kerop}@clarkson.edu

ABSTRACT

This study proposes the use of an innovative array of accelerometers for inertial tracking that is enabled through the use of a non-Cartesian hyper-coordinate frame. Traditional inertial tracking technologies employ an array of accelerometers and gyroscopes oriented in the orthogonal axes of the Cartesian coordinate system. The gyroscope sensors are responsible for deducing the relative orientation of the instrumented object, while the accelerometer measurements are double integrated to approximate the change in linear position relative to the local coordinate frame. Since the position determination is dependent on the orientation derivation, the accuracy and stability of the gyroscope sensors to a large extent determines the overall system performance. Consequently, high-performance gyroscopes are generally used in inertial tracking systems, thereby driving the system cost significantly higher. The proposed approach exclusively utilizes accelerometers in an innovative six axis orientation that, through linear algebra, resolves linear and angular accelerations. The functional layout is processed in the context of hyper-dimensional coordinates which ultimately produce an inherent vector redundancy when resolved in the Cartesian coordinate frame. This revised architecture is anticipated to alleviate many of the issues plaguing traditional inertial tracking that stem from the stability of derived orientation from gyroscope readings. In addition, the exclusion of gyroscopes from the design significantly reduces the unit cost of the system.

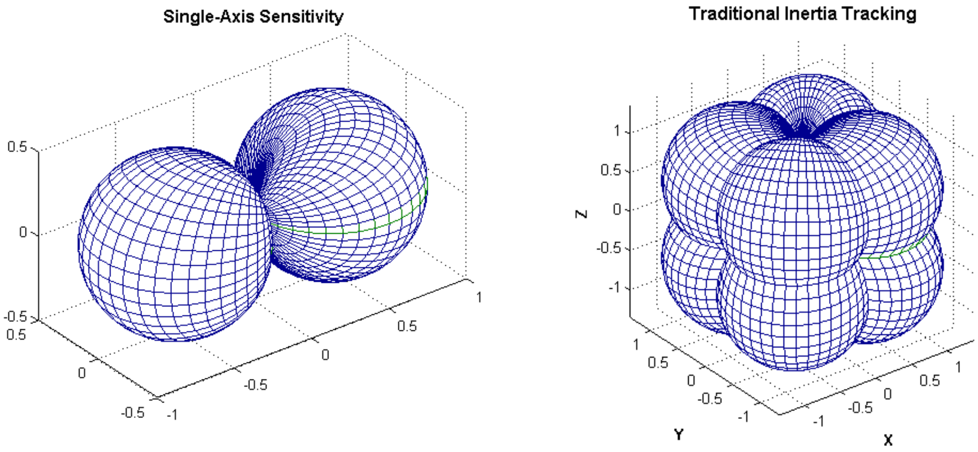
This paper additionally presents the development of a wireless system that incorporates the above described, unique array of dedicated sensors for inertial tracking to provide accurate determination of position and orientation of the sensor over time. The system permits access for additional channels of sensors for application specific monitoring tasks. This allows sensing on objects in motion and in regions or flow patterns that cannot be easily instrumented with traditional wired systems while maintaining knowledge of instantaneous position relative to the initial location. To date, the majority of wireless sensor network deployments have enabled instrumentation of widespread sites, such as civil structures, to alleviate the expense associated with the lengths of cable necessary to connect the sensors to a central acquisition station. The alternative approach sought utilizes the unrestrained nature of the wireless sensor to extend the use of this technology beyond static monitoring into applications in which the sensor node travels across an area without a priori knowledge of the sensor motion. Documentation of the hardware development of the proposed wireless sensing node as well as assessment of the system performance will be provided.

KEYWORDS: inertial tracking, wireless sensor networks, Synergetic coordinates

INTRODUCTION

The traditional approach to motion tracking through inertial sensing utilizes three orthogonal gyroscopes to measure angular velocity coupled with three accelerometers positioned along the gyroscope axes to record the particle acceleration. Integration of the angular rate measurements enables the derivation of the relative change in orientation and the development of a time-local coordinate frame for the accelerometers. The gravity compensated accelerations are then double integrated to approximate the relative position. Since the position calculation is dependent on the accuracy and stability of the orientation, there is very high demand on the performance of the gyroscope sensors. Additionally, the correction for gravitational acceleration is also dependent on the derived orientation, so drift and inaccuracy in the gyroscope measurements accumulates compounding errors in the tracking calculations. When the general specifications of MEMS-based gyroscopes and accelerometers are compared, the burden for maintaining the accuracy of the tracking system is heavier on the gyroscopes than on the accelerometers (Foxlin, 1998). Typically, to maintain sufficient accuracy for critical applications, high precision sensors, such as fiber-optic gyroscopes are often necessary, thereby driving the system cost substantially higher.

Consequent to the high cost introduced by precision gyroscopes, an alternate approach to the inertial tracking methodology is sought using only low-cost MEMS accelerometers. No less than 6 vectors must be utilized to derive rotational orientation and linear position. Coupling pairs of accelerometers equidistant along the orthogonal directions of the *xyz* coordinates would permit measurement of both linear and rotational accelerations through calculation of moment accelerations. However, this orientation results in greater sensitivity along off-axis angles with reduced sensitivity along the xyz axes. The resultant sensitivity distribution mirrors the traditional inertial tracking scheme, where the contributions of single-axis sensor sensitivities produce non-uniform system sensitivity (Fig. 1a). For the purposes of this study, we define the system sensitivity as the sum of directional sensitivities of each sensor axis. Defining the system sensitivity permits visualization of the directional characteristics of the sensor array. Each sensor axis is normalized to unit magnitude; sensitivities greater than one are produced as a result of directional redundancy through inter-axis coordination. The high degree of non-uniformity in the traditional inertial tracking layout may be an issue in promoting directional drift as there is a sharp slope in the system sensitivity near the axes. Consequently, even uniformly distributed noise may tend to produce significant skew as the effective system quantization is non-linear. It should be noted that the orthogonal gyroscope orientation will also produce this same sensitivity distribution relative to the axes of the gyroscopes.


Single-Axis Sensitivity

Traditional Inertia Tracking

Fig. 1. Non-Uniform System Sensitivity of Traditional Inertial Tracking Sensor Orientation

PROPOSED INERTIAL TRACKING METHOD

A new inertial sensor configuration has been developed using only MEMS accelerometers through application of a four-dimensional hyper-coordinate system. In addition to the significant reduction in system cost, the proposed approach results in greater and more uniform system sensitivity (Fig 2). The increase in magnitude of the system sensitivity results from a beneficial redundancy of the measurement axes, which will be apparent as the configuration is presented.

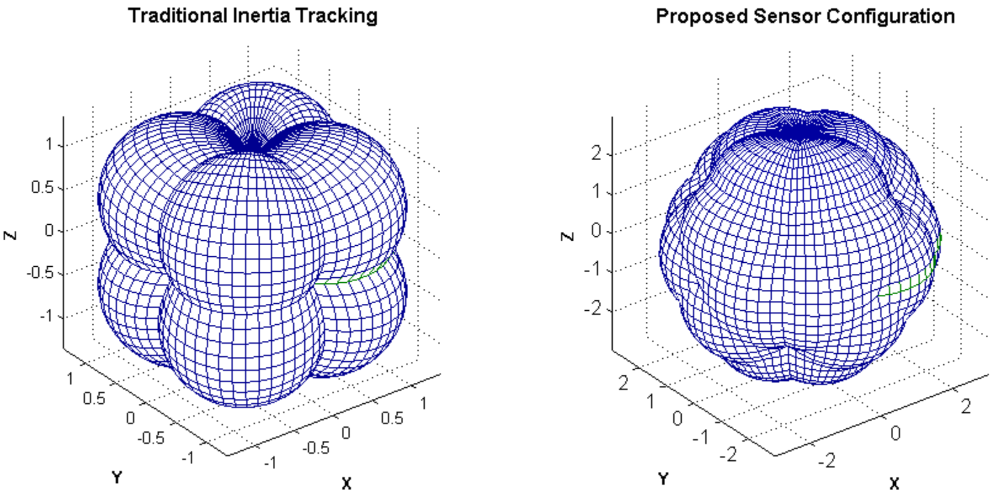


Fig. 2. Directional system sensitivity comparison between traditional approach and proposed method (note magnitudes)

The sensor layout was developed from the vectors of the minimum stable structural system defining volumetric space, the tetrahedron. The edges of a tetrahedron are a set of six vectors that are equilibrated linearly and rotationally. A simple orientation correction algorithm was also developed to enable consolidation of the six measurement axes onto only three orthogonal surfaces (Fig. 3). In effect, half of the axes of a tetrahedron are coupled with half of the vectors of the negative complementary tetrahedron. This permits three pairs of integrated dual-axes accelerometers to be utilized rather than six single axis units for reduction in system size and cost.

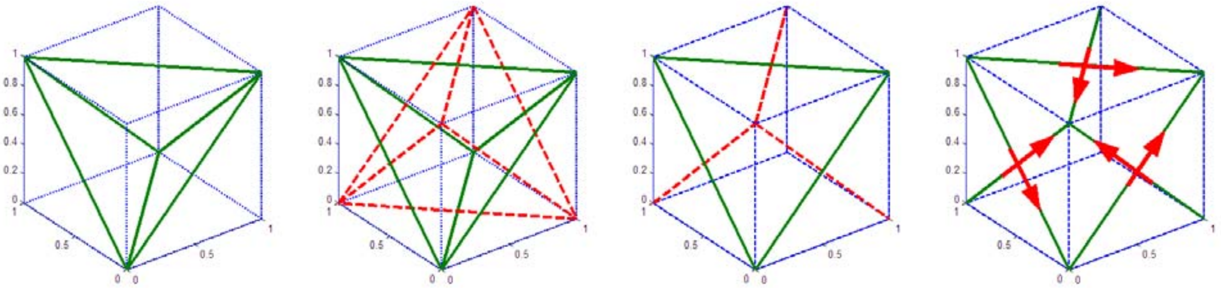


Fig. 3. Derivation of Alternate Axis Configuration: a) Tetrahedral vector equilibrium reinforces cube, b) Comlement of tetrahedron, c) Removal of redundancy in linear directions, d) Measurement axes of biaxial accelerometers in proposed configuration

While the vectors of the accelerometer axes are easily visualized in the 3D *xyz* Cartesian coordinate system, they function concisely, and were derived in reference to, the four-dimensional Synergetics coordinates developed by Buckminster Fuller (Fuller, 1975). The Synergetics space is not simply three-dimensional space with the fourth dimension as a non-spatial vector, such as time; rather, volumetric space is inherently four-dimensional, as proposed by Fuller. The coordinate axes of 4D Synergetic space are formed by the four vertices of the tetrahedron (Fig. 4). In fact, the vertices of the Synergetic coordinates correlate to closest packing of spheres and interrelate fundamental structural shapes found in nature, such as the icosahedron and octahedron. Although these vertices do not reap the benefits of orthogonality offered by Cartesian coordinates, they gain advantage through their 60˚ omnidirectional orientation. Consequently, all vectors are represented by at most 3 of the 4 vertices, or rather can be described independent of any one of the vertices, and consequently can be represented using only positive indices.

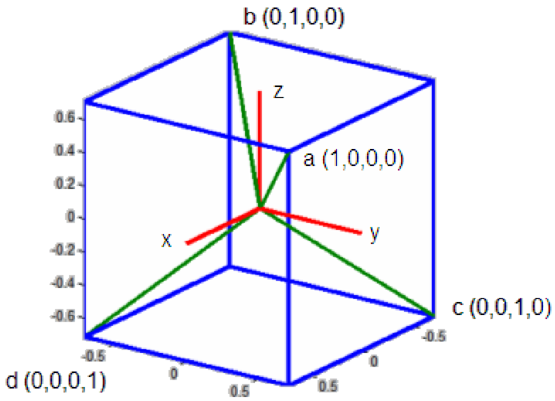


Fig. 4. Fuller's Synergetic Hyper-Coordinate Axes

For computational ease, the linear and rotational inertial accounting derived from the acceleration measurements should be performed using four-dimensional coordinate matrices. However, examination of the accelerometer axes orientation in reference to the three-dimensional vector space (Figure 3.d) illustrates the advantage gained through this orientation. In any of the Cartesian directions, there are equal components of four of the accelerometer axes, leading to a beneficial redundancy in the structuring. Consequently, every vector direction is equally represented by the sensor array resulting in more uniform sensitivity, as opposed to if axes are oriented in the *xyz* Cartesian axes. Additionally, rotations are measured about the four axes of the Synergetics coordinates, with three accelerometer axes orthogonal to and equally contributing to the rotation about each axis. Again this exceeds the redundancy of traditional three-dimensional inertial tracking whereby rotational motion is provided for three orthogonal, and therefore independent, axes.

The proposed approach to inertial sensing is similar in many respects to the traditional accelerometer and gyroscope approach in terms of the functional block diagram (Fig. 5). The fundamental difference is that six acceleration measurements are used to determine linear and rotational accelerations along and about the four axes of the hyper-coordinate frame. The resultant accelerations are then projected into the traditional *xyz* coordinate frame with inherent redundancy that functions essentially as an averaging of the measurements. Rotational accelerations are then double integrated to deduce the relative change in the node orientation. The local coordinate frame can then be adjusted for pitch, yaw, and roll. Since most MEMS accelerometers are mechanical units that, unlike piezoelectric accelerometers, include static accelerations in their frequency response, the static force of gravity must be subtracted or filtered from the linear accelerations prior to integration. Finally, the linear accelerations are double integrated to determine the node position relative to the previous time step.

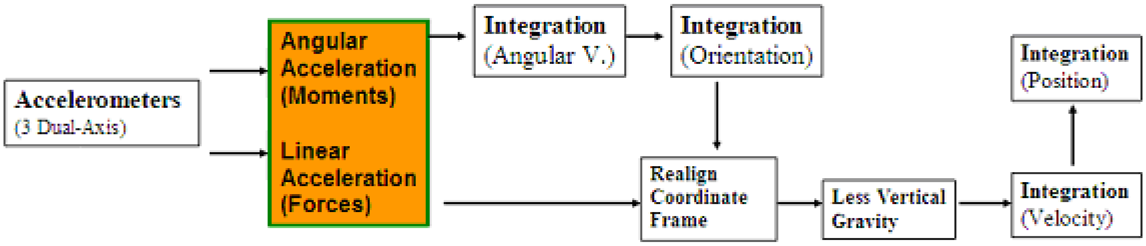


Fig. 5. Proposed Inertial Tracking Method

PROTOTYPE DEVELOPMENT

Currently, a hardware design for evaluating the proposed inertial tracking approach is under development (Fig. 6). The system consists of three low-cost MEMS dual-axis accelerometers interfaced with a six-channel simultaneous sampling ADC. The accelerometers feature a +/-2g full-scale range, complete DC to 2kHz bandwidth, and a low $30 \mu g / \sqrt{Hz}$ noise floor. Three pole analog low-pass filters are provided on each sensor channel for anti-aliasing of the signal prior to conversion. Analog to digital conversion is provided by the low-power 14-bit, 600ksps, LT1408 ADC. Additionally, the prototype system is interfaced with the TMote Sky wireless transceiver platform developed and marketed by the MoteIV Corporation. This enables wireless transmission of the sensor measurements for real-time feedback of the relative position and orientation of the system. Alternatively, this wireless transceiver platform offers sufficient onboard serial memory for local data logging in applications requiring higher sampling rates or in areas where wireless transmission is not feasible. Expansion pins are provided on the prototype board for connection of additional analog and digital signals. This permits sampling of additional task-oriented sensors through the internal 12-bit ADC on the microcontroller for application-specific purposes.

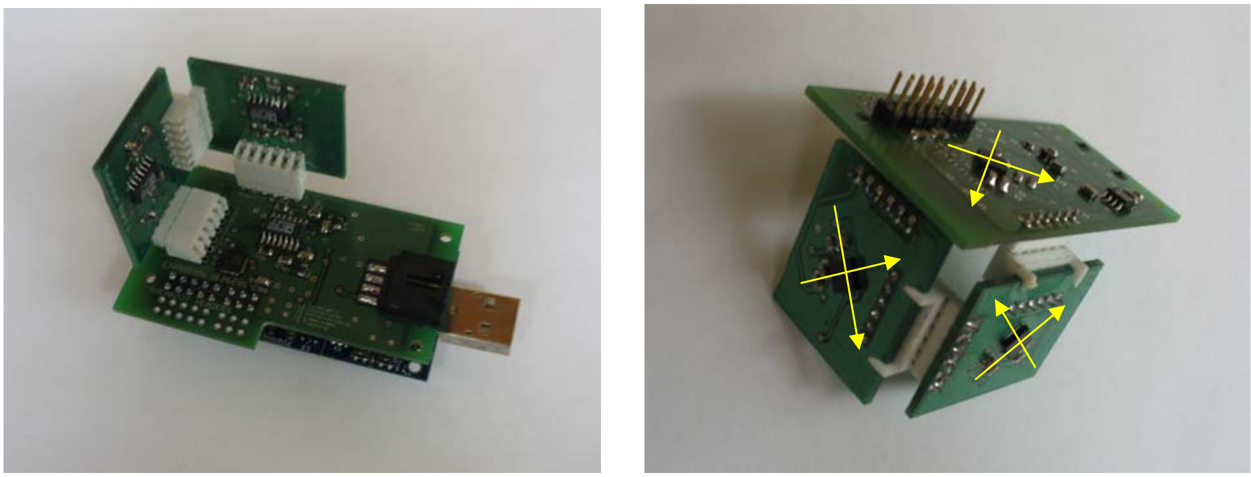


Fig. 6. Prototype Inertial Tracking System

The novel, four-dimensional approach to inertial tracking described above has been simulated using a software implementation of the vector restructuring and orientation/position derivation through user-input three-dimensional linear and rotational accelerations. Projected accelerations from the four-dimensional space accurately reconstruct the input acceleration vector with the noted redundancy for any combination of linear acceleration and rotation. Furthermore, the orientation and motion projections over time are reasonable representations of the corresponding input accelerations. This is expected as, aside from the measurement approach, the functional block diagram of the traditional accelerometer/gyroscope inertial tracking scheme is identical to the proposed six-vectored acceleration method. Further work needs to be performed on simulating the affect of sensor resolution and noise into the simulation to predict the stability and long-term accuracy of the new approach for comparison with the traditional method. However, the rotational acceleration derivation using the six-vectored accelerations depends to some degree on the physical dimensions of the accelerometer layout, as the rotational accelerations are dependant on the radius of the acceleration axis from the coordinate axis. Therefore, the physical size of the sensor nodes must be designed with regard to the desired orientation resolution.

CONCLUSION

The development of a wireless sensing device with integral knowledge of position and orientation through high accuracy inertial tracking has far reaching applications for real-time monitoring and unrestricted object sensing. A novel six-vectored acceleration sensing approach has been developed as a concise means of potentially alleviating many of the performance and cost issues plaguing traditional inertial sensing systems that incorporate gyroscope sensors. The proposed approach results in greater inter-axis redundancy and more-uniform system sensitivity. A prototype system is currently being developed with low-cost MEMS accelerometers and a wireless transceiver to evaluate the system performance and long-term stability. The concurrent development of a generic sensor interface to complement the motion tracking subsystem allows for application in a variety of monitoring tasks.

ACKNOWLEDGEMENTS

This research has been partially funded by the New York State Energy Research and Development Authority (NYSERDA). Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors.

REFERENCES

Foxlin, E., Harrington, M., and Altshuler, Y. (1998) “Miniature 6-DOF inertial tracking system for tracking HMDs. *SPI Helmet and Head-Mounted Displays III, AeroSense 98*. Orlando, FL. Vol 3362 April 13-14, 1998.

Fuller, R.B. (1975) *Synergetics: Explorations in the Geometry of Thinking.* MacMillan Publishing Co. New York.