Wireless inertial sensor for tumour motion tracking

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Abstract. A wireless diminutive inertial sensor being developed at Lancaster is capable of measuring position and orientation about three orthogonal axes. A real-time algorithm determines the six degree-of-freedom (6DOF) sensor posture, consisting of three components of dimensional position (heave, sway, and surge) and three components of rotational orientation (pitch, yaw, and roll). The objective of this study is to design an ultra-miniaturised version of this sensor that could be potentially implanted into tumours in order to help medical physicists track the motion of tumours and target the radiation accordingly.

1. Introduction
The objective of this research is to address a significant need that currently exists in medical radiotherapy. Radiotherapy is compromised by the mobility of tumours in the chest. The motion induced while breathing often makes it difficult to target tumours, meaning that patients often have to endure extended treatment times or carry out difficult breath-control techniques. A way to account for such motion is often desirable during radiotherapy treatments. By using tumour tracking, physicians can irradiate tumours more accurately without exposing the healthy tissue around the tumour to radiation.

The methods that have been developed to reduce the impact of respiratory motion in radiotherapy can be broadly separated into five major categories: motion-encompassing methods, respiratory-gating techniques, breath-hold techniques, forced shallow-breathing techniques, and real-time tumour tracking techniques [1].

The sensor presented here could be used by treatment planners, who have long appreciated that organs move and compensate for this by expanding the clinical target volume (CTV) by a margin to form the planning target volume (PTV) to which treatment is adapted [2]. Although this has been done many radiotherapy facilities do not currently have methods that explicitly account for respiratory motion.

Fiducial-based guidance has been used in combination with many of the aforementioned methods. This approach has the advantage that the implanted fiducials are comparatively easy to locate with automatic image processing tools, and the position determination involves relatively simple calculations [3]. Not surprisingly, most of the attempts to locate tumours using implanted fiducials require the use of an imaging system, and such fiducials are used as genuine real-time trackers situated in or near the tumour [4, 5, 6]. These markers are commonly implanted using techniques similar to biopsy procedures with a simple needle introduced under ultrasound guidance.

The first miniature, implantable device that could be tracked electromagnetically in three dimensions from outside the patient, was developed a few years ago [7]. The TULOC (Tumour
Location) system used trailing wires and therefore was not appropriate for human implant because of the invasiveness of the procedure which risked infections; nonetheless, it was successfully placed in a phantom and reported the potential of tumour tracking on the basis of transponder location. Other scientists [8], have reported on the performance of a wireless RF seed-tracking system (beacon transponders) for tumour localisation. This system is FDA approved and is now commercially-available. An optical/magnetic tracking system approach based on Electromagnetic implanted needles [9], and the PeTrack, a positron emission marker system [10], have also provided an alternative to the use of radiological imaging to track the tumour position.

2. Tracking background
One of the most important problems in tracking research today is to provide a fast, accurate, and unobtrusive method for reliably tracking of human motion. Such tracking is necessary because a user must continually be provided with three-dimensional computer-generated data that match the user’s three-dimensional real-world position and orientation.

The operating principles for the measurement of a moving object have been well established in the field of inertial navigation systems. Inertial trackers use accelerometers to measure the acceleration for object position and gyroscopes to measure the orientation of the object. Ideally, both are deployed in orthogonal triples (for 3D position in X, Y, and Z, and 3D orientation in roll, pitch, and yaw) in order to estimate 6D pose [11, 12]. Fig. 1 illustrates the general operation of an inertial navigation system (INS).

![Figure 1. Simplified strapdown inertial navigation performance. Each movement or rotation axis is independent of each other.](image)

Not until the advent of micro-electronic mechanical systems (MEMS) inertial sensors in the 1990s did the development of inertial input devices begin. Currently, various types of miniaturised macromachined elements are increasingly being integrated for different applications. In medicine, the use of MEMS comprises pressure sensors (gauges), pacemakers, human retinal prostheses, tactile sensors [13], and surgery [14].

3. Conceptual design of the sensor
3.1. Electronic Hardware
(i) Sensor Package: At the current development stage, onboard sensors include an ADXL330 Three-axis accelerometer, an ADXRS300 Single-axis gyroscope, and an IDG300 Dual-axis gyroscope.
(ii) Wireless: This work used an EB100-SER Bluetooth interface. The EB100-SER supports up to 230.4 Kbps continuous data rate and its transmission range is about 100 metres indoors when used with a proper antenna.
(iii) **Microcontroller:** The sensor control is based on the Microchip dsPIC30F2011 which operates up to 15 MIPS at 20 MHz, while supporting multiple AD conversions and having DSP capabilities.

(iv) **Tracking algorithm:** The algorithm used during both simulations and experiments, is illustrated in Fig. 2. This algorithm follows the traditional flow of information for a strapdown inertial navigation system. It was coded in Visual Basic for the simulation, and in Microchip C30 for the embedded dsPIC30F2011.

![Figure 2. Strapdown inertial algorithm.](image)

### 3.2. Inertial navigation configuration

From the point of view of the inertial navigation systems, the gyroscopes and accelerometers comprise an inertial measurement unit. The embedded microcontroller and the wireless transceiver are essentially part of a navigation computer. Fig. 3 shows the aforementioned configuration.

![Figure 3. Block diagram of the wireless inertial navigation system.](image)

### 4. Compensating the effect of gravity

As the strapdown system rotates arbitrarily about any axis, the orientation of \( \mathbf{u}_x \), \( \mathbf{u}_y \) and \( \mathbf{u}_z \) relative to \( \mathbf{X} \), \( \mathbf{Y} \), and \( \mathbf{Z} \) is given by (1).

![Figure 4. Representation of the Earth’s reference frame (black arrows) against the strapdown reference frame (grey arrows).](image)
\[ u' = u R_\phi \]  \hspace{1cm} (1)

Where \( u' \) is the rotated vector, \( u \) is the original components of \( u_x, u_y \), or \( u_z \) in vector format, and

\[
R_\phi = \begin{pmatrix}
t x^2 + c & t x y + sz & t x z - sy \\
t x y - sz & t y^2 + c & t y z + sx \\
t x z + sy & t y z - sx & t z^2 + c
\end{pmatrix}
\]  \hspace{1cm} (2)

Since the axes of rotation depend solely on how the sensor is rotated, \( R_\phi \) is a rotation matrix over any two points in space, where \( c = \cos \phi, s = \sin \phi, \) and \( t = (1 - \cos \phi) \). The components \( x, y, \) and \( z \) describe a unit vector on any of the axes of rotation \( u_x, u_y, \) or \( u_z, \) and \( \phi \) is any of the angles of rotation \( \phi_1, \phi_2, \) or \( \phi_3. \)

The analog output voltage of the accelerometer can be converted to acceleration using (3)

\[
A = \frac{[V_0 + V_G - V_Z]}{K_0}
\]  \hspace{1cm} (3)

where \( V_0 \) = output in volts, \( V_G \) = gravity offset, \( V_Z \) = zero output, and \( K_0 \) = accelerometer scale factor given in mV/g.

The compensation for the effect of gravity is performed by considering a gravity vector \( g \) on the vertical \( Z \) axis direction (see Fig. 4). The components of the \( u \) vectors are found using the angles \( \theta_1, \theta_2, \) and \( \theta_3 \) that correspond to the gyroscopic position of the inertial sensor.

Once any of the \( u \) vector components are found, the effect of gravity \( V_G \) can be accounted for on its corresponding axis by (4).

\[
V_G = K_0 \times \frac{g \cdot u}{|g| \cdot |u|}
\]  \hspace{1cm} (4)

It is assumed that the acceleration \( A \) will be zero when the sensor (in spite of being rotated) remains stationary. In movement, acceleration on the axes \( X, Y, \) and \( Z \) will be present.

5. Experimental setup

The prototype consists of two symmetrically-bonded PCB boards of size of 30 mm \times 20 mm \times 10 mm. With conditioned analog signals that are digitized, possessed, and transmitted wirelessly via Bluetooth; the power consumption is comparatively low, less than 20 mA at 3.3 V.

The sensor was located inside a custom-made gimbaled gyroscope (Lancaster University) for rotation tests (Fig. 5). Similarly, it was mounted on a 2-axis rig, capable of moving a small platform in two dimensions (Fig. 6). Each individual degree of freedom was tested independently.

6. Results

It can be seen from Fig. 7 that the accuracy of the gyroscopic reading is satisfactory when the device remains stationary, indicating that the algorithm interprets that there is no angular motion when the angular rate is zero. When the device is rotated, the algorithm determines the angular position acceptably. From Fig. 8, the performance of the lateral motion presented
Figure 5. The sensor in a gimballed gyroscope for testing.

Figure 6. The sensor in a 2-axis rig for testing.

an erratic response after the device is moved. During the first 3 seconds (when the device is stationary) the algorithm interpretation is consistent, nevertheless once the device is moved, the algorithm interpretation does not correspond to the actual position. During this experiment, the error ranged from few millimeters up to several centimetres. The error magnitude was more significant at faster movement rates.

Figure 7. Numerical integration of gyroscopic data: \( v \) is the angular rate of the given axis, and \( s \) represents the integration of \( v \).

Figure 8. Numerical integration of acceleration data: \( a \) is the acceleration of the sensor, and \( s \) represents the double integration of \( a \).

All 6 degrees-of-freedom readings drifted over time due to the accumulation of sumatory errors within the integrating algorithm. We tried to reduce this error accumulation by adding a better noise reduction technique to the algorithm; however, as the ADC acquisition speed could not be increased due to the limitation in hardware, the improvements were not sufficient.

7. Conclusion
In practice, making a 6DOF sensor based on MEMS that performs double integration is difficult to achieve - especially in real-time. In the field of human motion, most inertial signals are small, over the acceleration range \( 10^{-3} \) to \( 10^{-2} \) g’s. To obtain accurate signals, very accurate accelerometers and gyros are required.
We tested the accuracy of the sensor against practical measurements from our gimballed gyroscope and 2-dimensional rig. Each axis (DOF) was tested independently from the other 5 axes of motion. Our sensor is capable of measuring the static acceleration of gravity for tilt-sensing applications, as well as dynamic acceleration resulting from motion. Our first prototype has achieved tracking of all six degrees of freedom (position and orientation) with resolution better that 2 mm in position and 0.2 degree in orientation. It runs at 320 Hz with latency \( \approx 2 \) ms, needing no clear line of sight to anything else.

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