A MOBILITY DATA ACQUISITION SENSOR

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Abstract: With the recent developments in micromachining technology miniature sensors have become available that can be used in ambulatory monitoring systems for the continuous tracking of human motion outside of the lab. The multi-sensor array proposed in this paper consists of accelerometers (Analog Devices ADXL202), gyroscopes (Murata ENC-03J), magnetometers (Honeywell HMC1052) and a temperature sensor (Analog Devices TMP36). The accelerometers, gyroscopes and magnetometers are arranged orthogonally to measure in three dimensions. The principle of operation is estimation of orientation based on analysis of the outputs of all sensors. Accelerometers measure both static (gravity) and dynamic acceleration. As the gravitational field always has the same direction and value, 3 orthogonal accelerometer axes attached to an object give the direction of the local vertical acceleration. The magnetometers measure the magnetic field, another constant. The magnetic field is oriented to the North with an angle depending on the latititude of the monitoring site. These measures combined with the angular velocity of the gyroscope make determination of user activity possible. The objective of this mobility data acquisition sensor is to determine if reliable information about a user's activities can be obtained even in the absence of information on the sensors position and orientation.

Introduction

Real-time mobility monitoring has many applications from telemedicine to post-operative recovery and is a promising tool in clinical applications. With the recent developments in micromachining technology miniature sensors have become available that can be used in ambulatory monitoring systems for the continuous tracking of human motion outside of the lab. Current methods of mobility monitoring require a fixed placement site and the orientation of the sensor to be known before activities can be determined.

The concept of using accelerometers to assess human body movements was first suggested in the 1970's by Morris[1] and Smidt[2]. However such systems were cumbersome and the sensors used at that time were bulky and thus not suitable for ambulatory monitoring.

In 1990 Willemsen et al. [3] extracted the knee joint angle and angular velocities using eight accelerometers. The system used two metal bars attached to thigh and shank and a formula was derived to calculate joint angle. Unfortunately, the arrangement of the rigid rods required for application of the formula was too encumbering for daily application.

In 1993 and 1996, Veltink *et al[4],[5]* investigated the detection of static and dynamic activities using uniaxial accelerometers. They concluded that the static activities of sitting, standing and lying could be distinguished using one accelerometer mounted on the trunk and one accelerometer on the thigh. Furthermore they concluded that an analysis of the thigh accelerometer signal alone allowed distinction between static and dynamic activities to be made. Thus two accelerometers one mounted in a radial direction on the thigh and one mounted in a radial direction on the sternum, were shown to be sufficient to discriminate between sitting, standing, lying and movement.

In 1995, Bussmann et al. [6] using the same method concluded that if more postures or aspects of postures, for example, lying supine, lying prone or lying on the side, need to be distinguished another accelerometer mounted in a tangential direction on the sternum was needed.

The work of Veltink *et al*., Bussmann *et al*. and others has established that accelerometer-based mobility monitoring works over the short term in a controlled environment.

In 1996 Heyn et al. [7] investigated the kinematics of the swing phase of gait from a set of eight leg mounted uni-axial accelerometers and two gyroscopes. The leg-mounted sensors gave an accurate representation of all the angles, velocities and accelerations, however the number of sensors used makes the system cumbersome and impractical.

In 1997 Miyazaki et al. [8] used a single rate gyroscope and a simple symmetric gait model to calculate the length of stride and walking velocity.

In 1999 Tong et al. [9] developed a simple portable gait analysis system using uni-axial gyroscopes. It was found that there were problems with the derived signals from the gyroscopes if the subject changes direction or turns, which was due to the limited information content from the signal of a uni-axial gyroscope.

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In 1999 Luinge et al. [10] described a way to fuse the signals from three gyroscopes and three accelerometers to obtain an estimate of orientation that is both accurate and limited in integration drift. It was found that the combination of accelerometers and gyroscopes gives a considerable improvement in estimated orientatation from either sensor alone. Since accelerometers do not give information about rotation around the vertical, there will still exist integration drift around the vertical axis.

In 2000 Sagawa et al [11] used a 3D accelerometer and gyro attached to the toe to measure walking distance without the subjects' features such as stride length or asymmetric walk being known.

In 2001 Lee et al. [12] developed a method for detecting and classifying walking behaviors and counting the number of steps using a bi-axial accelerometer and a digital compass. In 2002 Lee[13] made further improvements by adding a gyroscope. The sensing apparatus was implemented in two separate modules, the leg module containing the biaxial accelerometer and the gyroscope and the waist module containing the compass. After some experimentation, it was concluded that these are the optimum positions for activity and that the system is also comfortable and provides unobstructed wearability. The proposed method can also recognize not only the activity but also the user's current status or pose.

In 2002 Najafi et al. [14] devised a new method of evaluating the characteristics of postural transitions. The system used a miniature gyroscope and their DWT technique was able to cancel the integration drift from a gyroscope. In 2003 Najafi [15] added an accelerometer to their previous system. The results demonstrated that a system based on only one kinematic sensor attached to the chest performs very well in monitoring activities.

In 2003 Veltink et al. [16] proposed and tested a three dimensional inertial sensing system for measuring foot movements during gait. It consists of two biaxial accelerometers, perpendicularly oriented such that a three-axial accelerometer is obtained and three perpendicularly oriented rate gyroscopes. It was found that foot movements could be reconstructed from the 3D inertial sensor signals such as to distinguish the change of foot movements during swing.

In 2004 Culhane et al [17] demonstrated that accelerometer based mobility assessment is effective for long periods in uncontrolled circumstances.

In 2004 Luinge et al. [18] described the design and performance of a Kalman filter to estimate inclination from the signals of a triaxial acceleromter. This is nearly twice as accurate as an estimate obtained by low-pass filtering of the accelerometer signals. A more accurate estimate of the inclination using ambulatory methods can be obtained using additional sensors like gyroscopes.

In 2004 Noury et al. [19] developed an ambulatory activity recorder using three accelerometers and three magnetometers. They identified such transfers as "sitting down" or "standing up" thus it was possible to make algorithms for detecting both walking and the transfers. More sophisticated movement such as "lying-to-standing were much more difficult to detect automatically.

The objective of this mobility data acquisition sensor is to determine if reliable information about a user's activities can be obtained even in the absence of information on the sensors position and orientation. This sensor is intended for placement in the user's pocket and aims to distinguish the activities of sitting, standing, lying and walking.

Materials and methods

Accelerometers are frequently used because they can easily be attached to a human body segment. These properties enable the ambulatory monitoring of patients during daily life however a problem with many accelerometers is that they suffer from a fluctuating offset. Another problem arises when an accelerometer is used as an inclinometer. It requires the acceleration to be sufficiently small in comparison to the gravity. This assumption may be valid under quasi-static conditions like the measurement of sway, but is violated during dynamic tasks. Despite the mentioned drawbacks of accelerometers, they are still suitable sensors. During the stance phase, when the angular acceleration is nearly zero, the inertial force is principally due to gravity, and the segment inclination can then be calculated. During the swing phase the angular acceleration affects the measurement and therefore inclination cannot be accurately calculated. A promising alternative is to use gyroscopes directly to measure the angular velocity without the signal being affected by gravity or any linear acceleration.

Gyroscopes can be used to calculate the segment inclination and theoretically the relative joint angle. Unlike an accelerometer a gyroscope can be attached anywhere to a body segment as long as its axis is parallel to the mediolateral axis: the angular rotation is still the same along this segment. The angular velocity is less noisy than acceleration since acceleration is the derivative of velocity and involves higher frequency components. Finally, there is no influence of the gravity acceleration on the recorded signal. Gyroscopes however, do have some weaknesses, the gyroscope is more delicate to use than an accelerometer and it is more sensitive to temperature and shock due to the mechanical fastening of the vibrating beam inside the sensor's case.

Although gyroscopes can be used to predict joint angle through integration of their signal one of the disadvantages of integrating the gyroscope signal is the introduction of drift into the measured signal, through the integration process. The zero-frequency component, referred to here as the DC component, of the signal could drift, and could change even when an object is not moving. Since a change in the DC component and a slow rotation at a constant velocity would produce the same signal, the drift of the DC component would be measured as a continuous movement of the object, and the error of integration due to this drift would grow without bound. Thus data obtained from integration can be distorted by offsets or any drifts and therefore

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powerful signal processing and filtering are necessary to cancel drift and movement artefact in the gyroscope signal.

In summary an activity monitor consisting of accelerometers and gyroscopes depends on combining their merits and compensating for their demerits. Success in assessing postures is a result of the fact that the accelerometer signal accurately reflects the component related to the orientation of the accelerometer with respect to gravity when there is no movement. When there is movement, both the orientation component and the acceleration component will change and then these two components cannot be distinguished from each other. Because movement induces changes in the accelerometer signal this can be used as a measure of the amount of movement. In contrast to accelerometers, gyroscopes measure one single component namely the angular velocity which is not affected by gravity or any linear acceleration. For this reason, systems combining the advantage of accelerometers (orientation during absence of movement) and gyroscopes (angular velocity during movement) have been developed to assess movements and the position of limb segments in ambulatory conditions. These combined systems are very accurate in assessing the orientation of a segment and tend to approach the performance obtained by camera systems [20] (errors smaller than 7% for angle, angular velocity, and angular acceleration). Adding earth-magnetic field sensors to the combined system of gyroscopes and acceleromters should increase the performance (accuracy of better than 1% RMS for position of Xsens device containing the three types of sensors) [21] as the magnetic field provides another orientation frame.

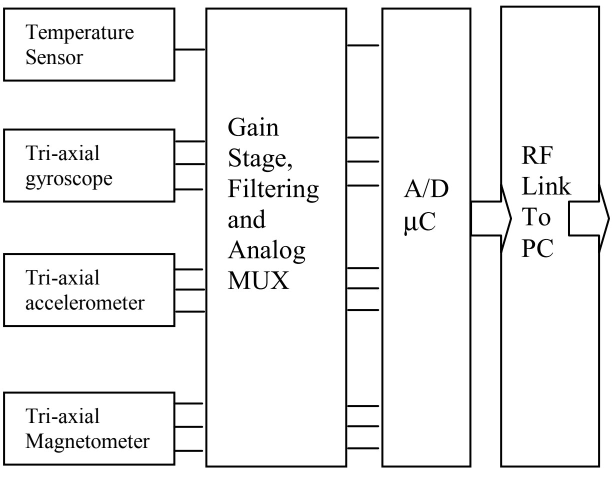

Figure1. The Mobility data acquisitio system

The multi sensor array proposed in this paper consists of a tri-axial microelectromechanical accelerometer, tri-axial micro rate gyro, tri-axial micro magnetometer, A/D converter, a micro controller, and RS-232. Fig. 1 illustrates the composition of the sensor array. An experimental prototype that was quite small and lightweight was developed. The prototype comprised of an Analog Devices temperature sensor the TMP36, two Analog Devices ADXL322 accelerometers, two Honeywell HMC1052 magnetometers, three Murata ENC-03J rate gyroscopes so as to form a three dimensional multisensor configuration. Readings from the temperature sensor are used to calibrate the magnetometer. Additional circuitry periodically samples all tri-axis sensors and transmitts the data through an RS-232 to a personal computer for post-processing. Software in the computer then processes the received sensor readings.

The ADXL322 is a low-cost, low-power, complete 2-axis accelerometer with a measurement range of ±2 *g*. The ADXL322 can measure both dynamic acceleration (e.g., vibration) and static acceleration (e.g., gravity). An analog output proportional to acceleration is available from the X_{FILT} and Y_{FILT} pins for the x-axis and y-axis respectively and the bandwidth may be set from 0.01 Hz to 6 kHz via capacitors C_X and C_Y. The typical noise floor is 200µg√Hz allowing signals below 2 mg to be resolved for bandwidths below 60Hz. The ADXL322 is an ultra small package (4 x 4 x 1.45 mm LFCSP) designed to accomodate the integration requirements of mobile phones and other portable devices for a variety of motion, tilt, and inertial sensing features as well as position and tilt sensing for PC and gaming peripherals such as mouse and joystick devices [22].

The ENC03J is an angular velocity sensor that uses the phenomenon of the Coriolis force, which is generated when a rotational angular velocity is applied to the oscillating body. The sensor's ultra small size and ultra light weight is made possible by using Murata's original, ultra small ceramic bimorph vibrating unit.

The HMC1052 is a two-axis sensor on one chip for compassing and position sensing applications. This device offers nearly perfect orthogonal two-axis sensing in a 3mm x 3mm x 1mm 10-pin miniature surface mount package (MSOP). The HMC1052 has a sensitivity of 1mV/V/Gauss, a wide field range up to ± 6 gauss and can operate on a supply voltage as low as 1.8V. Each of the magneto-resistive sensors are configured as a 4-element wheatstone bridge to convert magnetic fields to differential output voltages. Patented on-chip set/reset straps eliminate the effects of temperature drift and stray magnetic fields. Capable of sensing fields down to 120 micro-gauss, these sensors offer a compact, high sensitivity and highly reliable solution for low field magnetic sensing.

The TMP36 are low voltage, precision centigrade temperature sensors. They provide a voltage output that is linearly proportional to the Celsius (Centigrade) temperature. The TMP36 does not require any external calibration and its low output impedance and precise calibration simplify interfacing to temperature control circuitry and A/D converters. Supply current runs well below 50 µA providing very low self-heating – less than 0. °C in still air. The TMP36 is specified from -40°C to +125°C, provides a 750 mV output at +25°C and operates to +125°C from a single 2.7 V supply. The device has an output scale factor of +10 mV/°C and is available in a low cost surface mount package (SO-8).

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Discussion

There has been much activity in trying to find solutions for capturing gait information over large distances and outside a laboratory environment that can be of use in a daily life setting. Portable systems based on wearable sensors have been developed that have addressed some of the problems of the fixed systems but to be independent of a laboratory environment these sensors need to be patient-mountable, small, and unobtrusive, while providing accurate real-time information to facilitate efficient and precise control. Such systems should also offer repeatability and flexibility and provide enough appropriate information for a clinical assessment of the gait. Thus motion analysis using small sensors offers the best alternative for assessment of daily physical activity.

In general, systems have been developed to identify the type of activity but these methods are cumbersome because they used two or more different sites of attachment to the body and cable connection, reducing their applicability for long-term monitoring of physical activity, and in fact interfering with activities. A system using only one sensor or sensor unit attached to one specific body segment is preferential while still being able to identify the type of activity. A practical system must be small and easy to apply, and provide enough relevant information. Such a portable kinematic gait analysis system can be built using small sensors. It should consist of an inertial movement unit containing an array of movement sensors such as gyroscopes, accelerometers and magnetometers that can be worn at one specific site by an individual and used unrestrictedly in a daily life setting. The multi-sensor array unit offers better compliance as it will be discreetly placed in the users pocket unlike previous devices that are mounted ona fixed body site either over clothong or attached directly to the skin

Conclusion

The idea is to develop a sensor that is discrete, unobtrusive and comfortable to wear that does not rely on sensor orientation to determine activities. The eventual aim is to develop a self-contained unit where all calculations will be done on-board and user activity information will be displayed.

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