The Design of an In-Line Accelerometer-Based Inclination Sensing System

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***Abstract*—In this paper, we present a novel inclination sensing system, which is composed of an inexpensive and low power microcontroller with a 3-Axis digital accelerometer. Accelerometers have been widely used to determine the inclination or tilt angles of a system by calculating angles between gravity vector and its three axes. However, the angle calculation is so complicated that in most previous research work it is usually finished off-line on a more powerful computation resource, such as a PC/PDA or implemented with expensive memory lookup-tables. In the proposed system, we design and implement a novel algorithm on the embedded microcontroller such that the system is capable of transferring the raw data of the accelerometer from motion domain to angular domain in-line, such that the system can provide the inclination or tilt angle information alone in real-time.**

I. INTRODUCTION

Nowadays, the inertial sensing has been widely used in many fields of applications. Indeed, the 4 out of 5 modes of motion sensing: *acceleration*, *vibration*, *shock*, *tilt*, but only not *rotation*, are actually different manifestations of acceleration over different periods of time [1]. As a result the accelerometer-based body sensor networks are developed and mainly targeting for medical applications driven by the increasing demands of tele-care due to the aging of the societies and lifestyle changes.

When the net acceleration or force on the device node over time is gravity, the projections of the gravity vector on the axes of the accelerometer can determine the static inclination or tilt angles of the node by calculations of mathematical trigonometric functions from the projected gravity vector on the 3 axes of the accelerometer. The information is typically utilized in the posture monitoring applications, as in [2], several accelerometers are placed along the vertical axis of the spine in the mid-sagittal plane for collecting data indicating the angles of spinal movement and posture in daily life. And also some position monitoring applications, such as head's angle position monitoring after vitreoretinal surgery [3].

However, the calculations of these trigonometric functions are usually so complicated that their computation time will cost a lot of when implemented in a low cost and low power microcontroller. Hence, most current research works adopt offline computations [3], streaming the raw data to PC/PDA for computation [4][5][6], and table look up [7]. Indeed, the offline computation approach could not identify the tilting information within the system; as a result, the system does not have the capability for early detections for some critical behaviors and to generate real time warnings. The streaming approach has the concerns of excessive RF signal transmission; therefore, higher system cost and higher power consumption are involved. Table look up approach requires huge memory space for table storage and produce higher system cost. For example, LIS331DLH, a 3-Axis digital accelerometer from STMicroelectronics, Inc., has 12-bit fixed resolution for ±2g range. It would require 11-bit for ±1g sensing range on each axis. In theory, the length of gravity vector calculated by raw data from accelerometer is 1024. Even if the angle is represented in a byte, it will require a table size of 8 Gbytes ($2^{11} \times 2^{11} \times 2^{11}$ bytes) to reach the maximum resolution and sensitivity. This is not feasible on typical microcontrollers which usually only have few hundred Kbytes or even less of flash or ROM on chip.

In this paper, we present a novel inclination sensing system which implemented with the proposed CORDIC-based low complexity and memory-less algorithm [8] on a low cost and low power microcontroller and a 3-axis digital accelerometer, LIS331DLH. With the proposed system, the collection of raw data from 3-Axis digital accelerometer, the three angles' calculation, and the data sending out through UART all can be finished within every sampling period in this closed embedded system time and hence the system is capable of performing tilting sensing in-line and in real-time. As a matter of fact, the computation time of the proposed algorithm is almost only 1/3 of the computation time using mathematics computations on the microcontroller used.

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II. ACCELEROMETRY-BASED TILTING SENSING AND THE PROPOSED ALGORITHM

A. *Accelerometer-Based Tilting Sensing*

When a 3-axis accelerometer is used for inclination sensing, the orientation (inclination and tilt angles) of the device can be determined through domain transformation as illustrated in Fig. 1. In the angular domain, Φ is the angle between the gravity vector (1g field) and the z-axis, θ is the angle between horizon plane (0g field) and the x-axis, and Ψ is the angle between horizon plane and the y-axis.

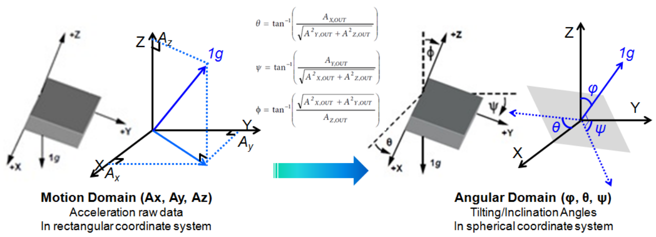

Figure 1. Domain transformation for tilting/inclination angle calculations

The mathematical equations to transform from the acceleration raw data in motion domain to angular domain for tilting/inclination angles information are described in (1)

$$\theta = \arctan\left(\frac{Ax}{\sqrt{Ay^2 + Az^2}}\right)$$
$$\psi = \arctan\left(\frac{Ay}{\sqrt{Ax^2 + Az^2}}\right) \quad (1)$$
$$\phi = \arctan\left(\frac{\sqrt{Ax^2 + Ay^2}}{Az}\right)$$

B. *Proposed Algorithm for Tilt Angle Indentification*

The proposed memory-less and low complexity algorithm called CGU tilting angle identification algorithm which is based on the 2D CORDIC [9] operations for in system tilting angle identification. Using 2D CORDIC operations supplants the complex multiplication, division, and square-root operations required in the original trigonometric functions with only basic adders and binary shifters [10] for rotation of a 2D vector through a sequence of simple elementary rotations.

The algorithm is to calculate the angle between a 3D vector and one of the three axes. Taking the identification of the angle Φ for example, Fig. 2 illustrates the algorithm. The algorithm is conducted in two phases. Phase I, Fig. 2(a), is to rotate 1g vector along Z-axis and have its projected vector on X-Y plane aligned to X-axis, and forms g' vector. The ration is performed by 2D CORDIC on X-Y plane with initial 2D vector (A_x, A_y) and final vector $(A_x', 0)$. The iterative equations are shown in Fig. 2(a) and the rotated angle η and $A_x' = \sqrt{A_x^2 + A_y^2}$ are accrued. Phase II, as shown in Fig. 2(b), is to rotate g' vector on X-Z plane and have it aligned to X-axis. The rotation is performed by 2D CORDIC on X-Z plane with initial 2D vector (A_x', A_z) and have it aligned to X-axis. The iterative equations are shown in Fig. 2(b) and the rotated angle δ is acrued through CORDIC operations and $\Phi = \pi/2 - \delta$. As you can see, the inclination and tilt angle, Φ, are obtained with simple shifting and addition operations only by this proposed algorithm.

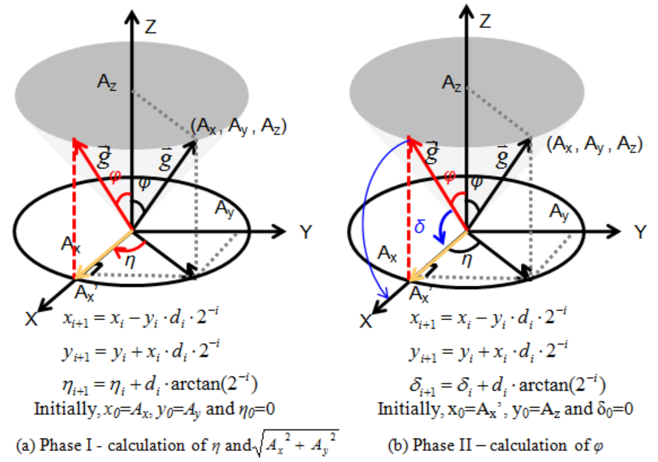

Figure 2. CGU Tilt Angle Identification Algorithm (a) Phase I (b) Phase II

Similarly, the same algorithms are performed twice more to calculate the tilt angles, θ and Ψ.

III. THE SYSTEM DESIGN AND PERFORMANCE EVALUATIONS

We have implemented the algorithm described in Section II.B on the embedded system which will be presented in this section and the computation time of the algorithm as well as the accuracy of the results are also carefully evaluated.

A. *The Hardware System Design*

The key part of the hardware system is a MCU (microcontroller unit), ADuC7020 form ANALOG DEVICES Inc., which is based on ARM7TDMI core. One three-axis digital accelerometer inertial sensor: LIS331DLH from STMicroelectronics Inc. is being tested. However, the sensor board is detachable and is connected to the system through I²C interface. Hence, the system is not limited to use LIS331DLH, and, in fact, we have also tested another three-axis digital accelerometer inertial sensor, ADXL345 from ANALOG DEVICES, Inc. to compare their performances on resolution, sensitivity, etc. The system block diagram is shown in Fig. 3.

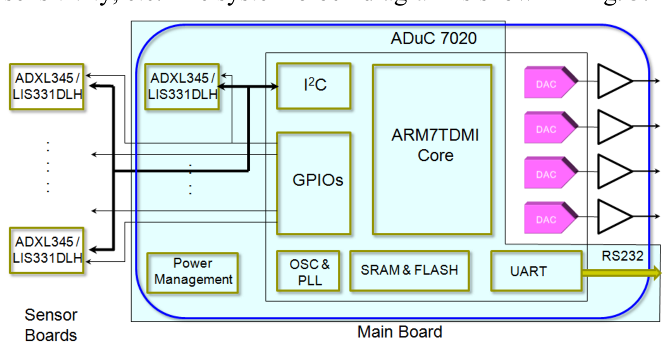

Figure 3. System Block Diagram.

LIS331DLH is an ultra low-power high performance three axes linear accelerometer. It has three dynamically selectable measuring ranges: ±2g, ±4g, ±8g, and with the ±2g range, it can provide its best sensitivity (1mg/digit). ADXL345 has four user-selectable measuring ranges: ±2g, ±4g, ±8g, ±16g. It can provide its best sensitivity (3.9mg/LSB) with ±2g range. In order to get the maximum resolution and sensitivity, LIS331DLH with ±2g is chosen. Besides, there is a low pass filter in LIS331DLH, which can remove some high-frequency noise, and this is also an important reason we chose it.

The firmware executed on the MCU ADuC7020 is developed in C language under uVision4 IDE. The maximum frequency that the MCU can run is 41.76MHz, however, for the power concern; we set the MCU core clock at 5.22MHz. The communication between MCU and the three-axis accelerometer is through I^2C bus. The sampling rate of the accelerometer is set to 100Hz in our testing and therefore the MCU gets the rectangular coordination (x, y, z) of gravity vector from a 3-Axis digital accelerometer every 10 ms, data are transformed to angular domain for tilting angle identifications, and the last, MCU sends the calculated angles out through RS232 at the baud rate of 115200.

B. Accuracy and Timing Cost Evaluation

Since our proposed tilting angle identification algorithm is CORDIC-based, the number of iterations executed in the algorithm will greatly impact the accuracy of the results. In our previous studies [8], we shows that the more iterations been executed in CORDIC operations, the better accuracy that we can get. However, the execution time of the proposed algorithm is expected to increase as the number of iterations increases. Hereby, we test different number of iterations in CORDIC operations from 4 to 12, and compare the calculated angles from the system with mathematical calculations on PC side to verify is accuracy and also measure the execution time of our tilting angle identification algorithm in the system by logic analyzer. We have summarized the results in Fig. 4.

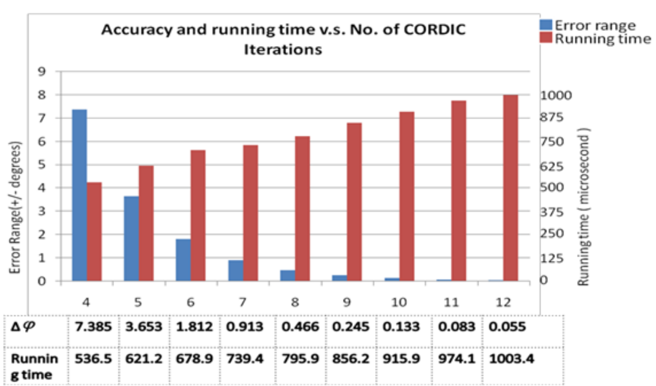

Figure 4. Accuracy and timing cost evaluation with varied number of iterations in CORDIC operations

From this comparison, we observe that the accuracy of the proposed algorithm can be very good when the number of iterations is big enough. However, the timing costs also increase as number of iterations increases. We believe that the accuracy of +/-0.466 degree is good enough for most of the applications for 8 iterations, and time cost of 795.9 microseconds is still way faster than the one from original trigonometric functions, which will be discussed next.

C. Performance Comparison

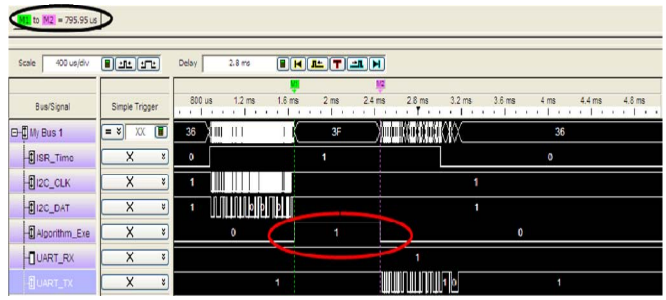

Figure 5. The execution time of the proposed algorithm.

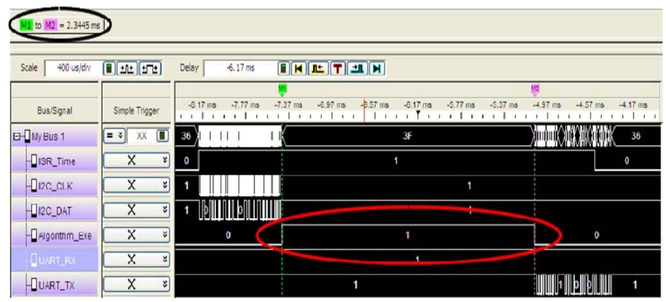

Figure 6. The execution time with mathematical equations.

The development system of uVision4 supports some mathematical functions for ADuC7020. So, we have further compared the performance of the system with proposed CGU tilting angle identification algorithm with the system implemented with mathematical equations. We use logic analyzer to measure the execution time of these two implementation and the captured screens are shown in Fig. 5 and Fig. 6 respectively. The measured execution time of the trigonometric functions in the system is about 2.3445ms as shown in Fig. 6. Comparing with the execution of the proposed algorithm in the system, 795.95us, as shown in Fig. 5, it is about 3 times slower than our proposed algorithm.

Even the mathematical implementation in the system is feasible under our testing case (ADuC7020 at 5.22MHz and 100Hz accelerometer sampling rate), there are some other tasks need to be done with one sampling period. For example, the I^2C communication with single accelerometer takes about 780 us, and RS232 transmission is about another 555 us. Thus, it would cost about 3.6 ms totally from data collecting to data sending out if angles are calculated by original trigonometric functions.

As a result, it leaves not much room for implementing some detection algorithms for the specific medical applications, and also not feasible when multiple accelerometer sensors are required neither in the cases of higher sampling rate is required, i.e. 500Hz sampling. On the other hands, the presented system implemented with our proposed algorithm can provide more room for in-line detection algorithms in various applications and also more suitable for faster sampling rate and multiple sensors requirement applications.

IV. Conclusions and Future Work

In summary, the tilt angle identification algorithm proposed could be performed in a low-cost and high-portability closed embedded system as presented in this work. With the system, early detection and prevention on some critical behaviors are feasible to implement. Real time warnings and actions can be taken for some emergent situations in some medical applications.

We will further apply the presented system on the studies of transient spontaneous remission of the patients with obstructive sleep apnea syndrome. How the transient spontaneous remission happens is still unclear in clinical studies. It might be causing from body position changes, arousal, and head position changes. Unfortunately, the existing polysomnography is incapable of measuring head position with high accuracy. To help on the study of how the head position relates to the transient spontaneous remission of obstructive sleep apnea syndrome, the system presented could work with polysomnography by attaching the sensor board on the forehead of the patient and the system can transfer the head positioning information to the polysomnography for the real-time and in-line diagnoses.

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