Motion Processing:

The Next Breakthrough Function in Handsets

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Introduction

Cell phone manufacturers are seeking new functionality to differentiate their mobile handsets and update relatively primitive interfaces with too many buttons and menus. Motion processing is emerging as the only solution that can deliver a new user interface and experience that will make a specific mobile handset stand out. *MotionProcessing*™ technology from InvenSense™ can bring about next generation gesture-based user interface (UI) for menu navigation, enables mobile authentication, enhances location based services (LBS), delivers an immersive gaming experience and improves camera image stabilization (IS). But in order to do this credibly, existing solutions based purely on 3-axis accelerometer motion sensing are not sufficient. There is a need for full, six degrees of freedom (6-DoF) motion processing that can precisely translate human motion for the various applications. This paper provides an overview of a microelectromechanical system (MEMS) based 6-axis motion processing solution that can enable these emerging motion-based applications for handsets.

Mobile Phones Sense Motion Today

Since Apple introduced the iPhone™ and demonstrated tilt control enabled by MEMS accelerometers in 2007, it has sparked a revolution and raised the bar for mobile apps across all platforms. iSuppli reports that 27% of the cell phones produced in 2009 contain a MEMS accelerometer, due to their inclusion in the iPhone and other popular smart phones[1]. The accelerometer detects motion when the phone is turned from portrait to landscape and changes the display accordingly. The 3-axis MEMS accelerometer is also used to control many games, power management and shake modes to control music shuffle, undo, pedometers and a host of context-aware apps.

While accelerometers provide basic motion sensing for simple orientation and tilt applications, they have limitations affecting accelerometer operation and performance in more complex applications, such as handwriting recognition or image stabilization where up to 20 hertz of hand jitter must be detected. Accelerometers can only deliver the sum of linear and centripetal acceleration, gravity and vibration. It is at its best when movements are static or close to 1 hertz. Extracting a single element of linear motion information from the accelerometer is not feasible without an additional sensor, such as a gyroscope. iPhone 3GS™ and Google Nexus One™ adopted the digital compass to provide yaw, and the accelerometer detects tilt to compensate the compass. The digital compasses used in these handsets use a low-cost Hall-Effect sensor architecture. Hall sensors have the advantage of a simpler fabrication process than with other architectures, but the magnetic sensitivity of the final product is so low that the performance is severely impacted. The calibration values for the compass drift easily, requiring the end user to periodically execute a series of movements to recalibrate the compass. Other compass architectures may be better, but with the penalty of a higher cost and larger size. In addition, even a good compass is limited in how well it can measure heading due to interference from magnetic disturbances in the device and in the outside environment.

Gyroscopes, also called angular rate sensors, measure how quickly an object rotates. Gyroscopes are the only inertial sensors that provide accurate, latency-free measurement of rotations without being affected by any external forces, including magnetic, gravitational or other environmental factors. This rate of rotation can be measured along any of the three axes, shown in Figure 1: X (roll), Y (pitch) and Z (yaw). Adding gyroscopes to the sensor mix will allow algorithm designers to take advantage of a pure measurement of angular velocity that cannot be delivered by compasses or accelerometers. This measurement allows for accurate pitch and roll measurements when combined with an accelerometer, and these measurements can be used to more accurately tilt-compensate the compass. The introduction of silicon MEMS-based technology has allowed development of new MEMS gyroscopes that are no longer cost-prohibitive for consumer electronics and are suitable for achieving a challenging industry cost target of less than one dollar per axis, while meeting the package size and the appropriate sensing accuracy to become suitable for mobile phones, game controllers, remote controls and portable navigation devices.

How Gyroscopes Improve the Handset User Experience

iPhone revolutionized the user experience of cell phones in many ways. In addition to tilt control from accelerometers, iPhone provides a new touch panel user interface (UI) that allows the user to flip the menu pages by sliding a finger, or zoom in/out of the viewing area by

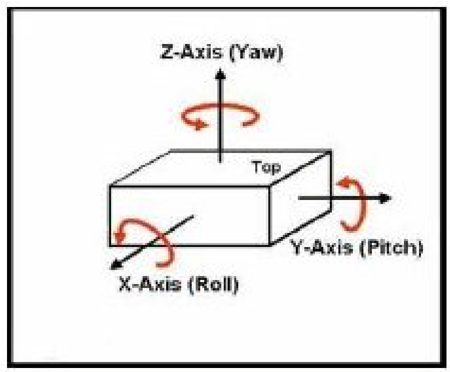

Figure 1. 3-axis gyroscope detects roll, pitch and yaw rotations.

"pinching" on the screen. The touch panel UI eliminates the need for cumbersome and tiny keypads on the phone, but it also creates new and different inconveniences for users.

For example, sometimes two hands are required to operate (e.g. zoom by pinching) and fingerprint smudges on the screen affect viewing quality.

By combining accelerometer and gyroscope, a more user-friendly UI can be created based on gesture recognition. Gesture recognition implemented on motion sensing devices allows a user to input commands or data by simply moving, shaking, or tapping the device. Figure 2 illustrates how picture zoom in/out can be done with a single hand, using gesture recognition UI to detect slight tilt movement. The gyroscope plays an important role in this tilt detection. As previously mentioned, smart phones use the accelerometer as a tilt sensor by isolating the signal due to gravity and use that as an orientation reference. However, this signal can only be isolated when the accelerometer is motionless; when there is movement, the output will be corrupted by linear and centripetal accelerations. This makes any tilt-based user interfaces or games extremely unstable. A common compromise is to low-pass filter the accelerometer to isolate tilt. This makes a correct assumption that, in human movement, linear accelerations will be transient, and can be filtered out. Unfortunately, it also makes the incorrect assumption that tilting movements are all slow, and as a result faster changes in orientation will also be filtered out. A low-pass filtered accelerometer makes an extremely poor tilt sensor for a user interface. A better solution is to combine the accelerometer with a gyroscope; this provides a rapid, accurate, high bandwidth tilt sensor. For applications in which dynamic tilt is desired but the fixed reference of gravity is not necessary (e.g. the zoom control), gyroscopes can be used without accelerometers.

Figure 2. Gesture recognition UI. User can zoom in the picture by simply tilting the phone.

Figure 3. Gyroscopes enable portrait-landscape mode switch when device is placed on the table.

Figure 4. Cube-based cell phone menu (LG Arena).

Figure 5. Answer the call by shaking the phone (KDDI Lab).

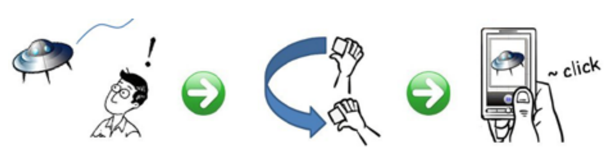

Figure 6. Gesture recognition UI: quickly turn on camera by hand waving the character "C".

Gyroscopes also improve the portrait-landscape display mode switch. Smart phones detect whether the picture should be displayed in portrait mode or landscape mode based on the gravity vector that it filters out of the accelerometer signal. Due to the filtering the user will experience a delay of about two seconds when mode switches. By incorporating gyroscopes the movement of phone rotation can be detected instantly and thus the display mode can be switched without delay. Gyroscopes also enable portrait-landscape mode switching when the device is placed on the table. The mode detection algorithm that only uses the accelerometer cannot distinguish horizontal orientation of the device; when the device is placed on a flat surface, the output of the 3-axis accelerometer is constant, where the z-axis aligns with the gravity direction regardless of the horizontal orientation of the device. Using gyroscopes, the transient rotation that changes the horizontal orientation will be reliably detected and thus the display mode switch can be activated accordingly. Figure 3 shows an example of horizontal portrait-landscape mode switch.

Figure 7. Various gesture recognition based technologies provided by InvenSense.

Gesture recognition will enable other more sophisticated cell phone use cases. Motion processing demonstrated in Figure 7 is one good example of how gesture recognition can bring benefits to cell phone user experience. *MotionProcessing* technology consists of several unique solutions: *MotionCommand*™ technology allows people to answer a phone call by simply shaking the phone two or three times. Short cuts can be created by recognizing numbers or characters such as hand waving a letter "C" to turn on the camera or a number "2" to initiate speed dial. *AirSign*™ technology can even capture the hand-waving "signatures" in high fidelity for identity authentication[3]. *TouchAnywhere*™ technology allows users to flip through pictures or select songs by simply tapping the finger on the phone body. Basically, gesture recognition UI provides users the freedom to easily interact with their smart phones with only one hand.

Motion Processing for Handset Gaming

In 2006, Nintendo's Wii™ revolutionized mainstream console games by adding a 3-axis accelerometer into the game controller. This new generation of console games introduced primitive motion sensing without controller tapping or shaking. To overcome the shortcoming of accelerometer-only motion sensing, in 2009 Nintendo introduced the Wii MotionPlus™ accessory, a dongle attached to the end of the conventional Wii controller with three gyroscopes integrated. According to Wii game developers, the improvement of motion sensing brought by the addition of a gyroscope is analogous to "the leap from the fidelity of VHS to that of Blu-ray"[2].

A similar paradigm shift is expected to be observed in the mobile phone handset market. In 2007, iPhone built in an accelerometer that opened up a new world of mobile gaming, introducing fun, engaging, and interactive applications such as virtual golf to racing games and music instrument players. The deficiency of motion sensing only by accelerometers, however, is more noticeable in mobile gaming than in console gaming. For instance, when the player is walking, or in a moving vehicle, the linear acceleration will degrade the capability to sense a player's real motion. To further improve gaming quality, adapting gyroscopes to mobile phones will be a natural trend in the near future.

Motion Processing for Location-Based Services (LBS)

Now that GPS is becoming a standard function in mobile phone handsets, it is expected that the next killer application for smart phones will be turn-by-turn car navigation and LBS. With LBS, the user will be able to use their phone to quickly locate the desired store, or particular goods in the store (mobile commerce), or friends in the neighborhood (mobile social networking). Store managers (or mall managers) will be able to post advertisements on the phone to attract customers or even collect fees for advertisements. Service providers will be able to increase ARPU (average revenue per user) through increasing air time usage or posting advertisements.

More and more LBS software applications have appeared on the market since 2009. Wikitude[5] is one of the pioneers, identifying the user's location by GPS and the heading by compass, presenting the user with data about their surroundings, nearby landmarks, and other points of interest by the technique of "augmented reality" (i.e. overlaying information on the real-time camera view of a smart phone). Wikitude was first launched in the Android Marketplace and is now available in the iPhone App Store. Yelp[6] has similar software that shows the location of a restaurant or bar, for example, and displays on-line reviews of the business.

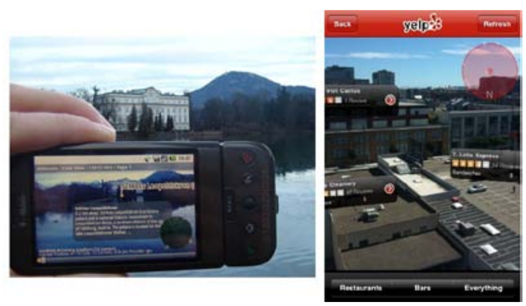

Figure 8. LBS apps on smart phones. Wikitude (left) displays wikipedia information of the landmark in the camera view. Yelp (right) shows the distance to nearby restaurants and their on-line rating and reviews.

Current LBS apps still have much room for improvement. First of all, the locations of the identified points of interests are only approximate, due to GPS resolution and compass accuracy, so the most common use of the current LBS apps is pointing the phone at a business the user is physically near and discovering its on-line rating and reviews, rather than finding businesses out of sight. Also, since the sampling rate of the compass inside the smart phone is slow (about 8Hz), the overlaying augmented reality information cannot catch up with the speed of the camera view angle change. As a result, when the user looks around, the overlay information often jitters around and sometimes even swings in and out of the screen.

Several activities are in progress to deliver a complete LBS solution. To improve the location resolution and accuracy of conventional GPS, augmented technologies such as differential GPS (DGPS), assisted GPS (A-GPS), and enhanced GPS (E-GPS) have been proposed. Companies are working on digital maps for pedestrian navigation. New technologies such as WiFi triangulation have also been developed. Signals from gyroscopes and accelerometers can integrate with a compass sensor to detect a user's 9-degrees-of-freedom (DOF) motion and provide precise alignment of augmented reality information with the camera view to deliver improved pedestrian navigation performance.

Commercially available pedestrian navigation systems for industrial and military applications, and other system design attempts within academia, give an indication of what is required in order to make a viable consumer pedestrian dead reckoning (PDR) system. It is clear that accelerometers, compasses, and gyroscopes will all be required. The accelerometers are used for long term measurements of pitch and roll, and for pedometer algorithms. The compass is used for long term measurements of yaw. The gyroscope is used as the underlying measurement of angular velocity. It is used to help the accelerometer separate out gravitational and linear acceleration components, to help the compass distinguish the Earth's magnetic field from ambient magnetic noise, and to help the sensors update their calibration parameters. A 9-axis sensor fusion algorithm (3-axis gyroscope, 3-axis accelerometer, and 3-axis digital compass) is illustrated in Figure 9.

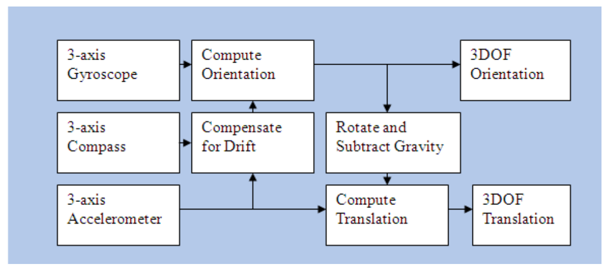

Figure 9. 9-axis sensor fusion algorithm. Information from gyroscope, accelerometer, and digital compass are integrated to generate 6 degrees-of-freedom (DOF) motion information (3-axis orientation and 3-axis translation).

Even with all of these sensors available, there is a major difference between the PDR system that handset designers envision, and today's existing dead reckoning systems. All successful dead reckoning systems are bolted to some known reference frame[7,8]. For example, most military PDR systems are worn on the belt; this ensures that the heading of the compass is equivalent to the heading of the user, with only a fixed angular offset depending on the location of the sensors on the belt. Other PDR systems have been designed with the sensors attached to the user's foot. While foot movement is more complicated than hip movement, foot mounted systems have the advantage that the foot is known to be motionless whenever it hits the ground, allowing for a zero velocity update.

However, handset designers really want to design a handheld PDR system that allows the handset to accurately track the user's movement, even while the display and controls of the handset are being actively used. Putting the motion sensors in the hand largely decouples them from the user's walking movement. Even with an accurate compass heading, the heading only indicates the direction that the handset is pointing in; this is not necessarily related to the direction that the user is walking. If the handset is not handheld, it will be in a pants pocket in the best case scenario and in a coat pocket or swinging handbag in the worst case. Providing a fixed reference frame would require removing the motion sensors from the handset and putting them in a separate Bluetooth module that is fixed to the user's body, and communicates wirelessly to a handheld device with a display. This is not an attractive solution for a handset designer.

Providing a more attractive solution will require both high performance sensors and out-of-the-box thinking. Visual feedback from the handset will be required to help the user understand how to hold the handset and what the motion sensors require. Machine learning approaches may be applied to learn an individual's gait (walking, running) pattern over time. Additional constraints must be provided for, such as map matching, including the use of indoor maps.

Wide Variety of Motion Processing Applications

As *MotionProcessing*™ technology continues to advance, smartphones will be used in more and more situations that are beyond current common phone use cases. In September 2009, Fujitsu announced a mobile phone application called ETGA Swing Lesson™. The application records and analyzes the user's golf swing movement by reading the accelerometer and magnetometer data from the mobile phone clipped on the user's waist[9]. Adding gyroscopes could improve the accuracy of captured body movement and detect subtle actions such as wrist turn. The user can hold and wave the handset and practice the moves anywhere. The benefit that motion processing brings to learning and education is not limited to sports; BMW is adopting the augmented reality technique to show different layers inside new model cars and teach mechanics how to conduct repair (Figure 11)[10]. Once the technology is deployed to school classrooms, the students will be able to use their camera phones to view virtual 3D models in science, art, biology and interior design classes.

Health care is another area where motion processing can contribute to advanced applications. There are already applications that read the accelerometer data and turn mobile phones into pedometers. With high sensitivity gyroscopes, the mobile phone will be able to detect minute body vibration and thus measure heartbeats or EKG when the user is simply holding the device in hand or putting it in a chest pocket. The protection of personal safety will also be improved with motion processing; for elderly care and emergency 911, the pedestrian dead reckoning technology can be used to track people's location and the phone can be set to automatically dial a hospital or 911 when elderly people walk to dangerous areas or stay motionless after a period of time.

Figure 10. Screen shots of mobile phone app "ETGA Swing Lesson" by Fujitsu.

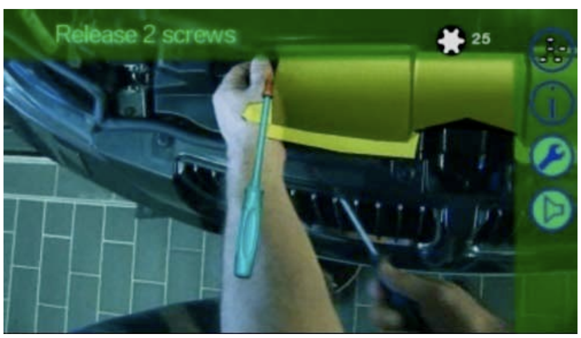

Figure 11. Augmented reality: on-screen information (green) assists mechanics to repair the car (BMW).

Motion Processing Design Considerations

Engineers adopting 6- or 9-axis motion processing functionality within handset applications are faced with the choice of either assembling gyroscopes and accelerometers from multiple sources, or selecting a fully integrated solution from a vertically integrated motion processing supplier[11]. There are merits and challenges to each approach. Motion processing product selection should consider the following interoperability points to maximize the value of motion processing functionality when the design includes multiple applications such as image stabilization, gesture recognition, mobile gaming, authentication, and navigation.

1. Each application requires a different gyroscope full scale output and data sampling rates.
2. Anti-aliasing measures must be employed to ensure motion data accuracy through the use of low-pass filtering that is specific to the particular app.
3. Accurate timing data is essential to determine the angular data calculations of the gyro through mathematical integration.
4. The drive, sense and harmonic frequencies of gyroscopes should be designed not to interfere with each other or any other frequencies within the system.
5. Synchronous sampling of the accelerometer, gyroscope, and digital compass data will ensure high-quality position coordinate information.
6. To alleviate computation and communication loading of a host system, it is desired that motion sensors possess processing power to integrate multiple sensors and to extract higher-level motion information (e.g. shake, tap).
7. Handset designs are very sensitive to size, power consumption, and cost. The motion processing solution that provides the smallest IC footprint, least power consumption, and lowest cost will be the most advantageous.

The Asahi Kasei (AKM) AK8976A is one of the early integrated sensor solutions successfully applied to the handset market. The 4.5mm x 4.5mm x 0.9mm LCC package contains a 3-axis accelerometer and a 3-axis Hall-effect digital compass. It has been included in the design of the HTC/Google G1 phone since 2008. In January 2010, STMicroelectronics announced a similar 6-axis product (LSM303DLH) with a slightly larger package size (5mm x 5mm x 1mm) but superior sensing capability (ST licensed Honeywell's Anisotropic Magneto-Resistive (AMR) compass technology). However, neither of the above mentioned products contains gyroscopes or on-board processing capability.

The InvenSense MPU-3000™ is the world-first 3-axis digital gyro with on-chip intelligent motion processing capability. At a size of 4mm x 4mm x 0.9mm, the gyroscope easily fits into any cell phone platform. The digital motion processor (DMP) is a custom-designed digital signal processing unit embedded inside the MPU device. It receives both gyro signals (internal) and accelerometer signals via a secondary I2C interface to perform advanced sensor fusion and motion processing. The processed motion information is forwarded to the host processor via the primary I2C interface. MPU-3000 is also equipped with a FIFO to buffer the complete data set, which reduces the timing requirements on the host application processor. One advantage of DMP is that, while the gyroscope samples data at a high frequency, it provides a scalable data output rate depending on the application requirements of the host processor. For example, the DMP may sample the gyro and accelerometer signal at 200Hz to recognize a walking step, but it only needs to output the recognized stride, orientation and number of steps to the host processor at a rate less than 1Hz.

More sensor fusion and motion processing algorithms can be run on the host processor. The MPU-3000 includes a software library called the Motion Processing Library™ (MPL). It contains algorithms such as compass sensor fusion, calibration, GPS integration, and more.

So far there is no gyroscope IC that integrates with other types of inertial sensors. However, as MEMS technology progresses, it is expected that there will be a single-chip 6- or 9-axis IMU for the handset market.

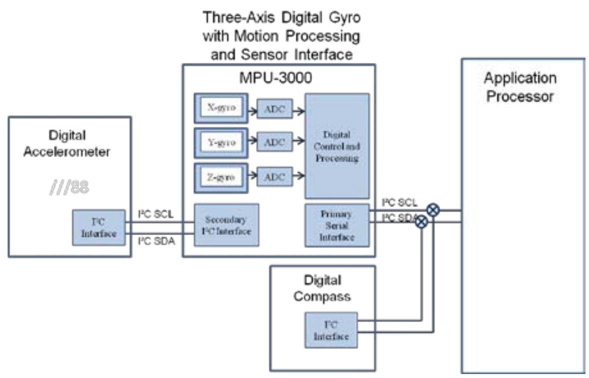

Figure 12. 9-axis motion processing solution. InvenSense MPU-3000 3-axis MEMS gyroscope has I2C interface to receive signals from other sensors like accelerometer, and also has processing power to extract motion information (tap, shake, etc).

Conclusion

In recent years the advances in MEMS technology have made significant improvements on the size, cost, and power consumption of inertial sensors, enabling the handset market to create motion-aware applications. With the combination of gyroscope, accelerometer and compass, a highly accurate, robust and latency-free motion processing solution can be established to revolutionize the way people use mobile phones. A gesture recognition based user interface will allow users to access their phones in a very easy and intuitive way most of the time with only a single hand. The inclusion of gyroscopes has raised the accuracy of motion capture to the degree that air signature authentication is possible, and also has brought the user experience of motion-based mobile gaming to a whole new level. Motion processing will also play an important role in the booming mobile commerce and location based service application market. Higher precision position estimation can be achieved and better augmented reality experiences will be provided.

About the authors

Steve Nasiri is CEO of InvenSense and founded the company in 2003. As a 30- year veteran of the MEMS industry, he developed the novel product concept known as, "Nasiri-Fabrication" and has authored over 50 patents (issued and pending) and many articles in the MEMS field.

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