A HARDWARE FRAMEWORK DESIGN FOR 3D MOTION SENSING, DETECTION AND ESTIMATION

Ersin Özkan, Cem Küççük and D. Turgay Altılar
Department of Computer Science and Institute of Informatics,
Istanbul Technical University, 34469, Maslak, Istanbul, Turkey
{ozkaner, kuccuk, altilar}@itu.edu.tr

ABSTRACT

Sensing and measuring position and orientation change of an object and modeling its motion are both challenging and attractive research areas. Motion detection may be applied to various applications such as stabilization of mechanical and electronical systems, simulation of real world actions in 3D virtual environments, human-computer interaction and multimedia devices. IMUs (Inertial Measurement Unit) are generally used to detect motion of attached object or system. However, they can be considered as small sized black-boxes with limited features at high prices. This paper presents a practical approach to design an inertial measurement system including different sensor combinations at low cost. The system will be used to test performance of different sensor combinations. Another purpose of the system is realizing inertial measuring unit of any kind of project at low cost. Final design with fully working hardware and software can easily be applied to target project. Design characteristics of such a system are listed and main properties of the developed system are presented. Hardware and software structures, communication methods, user interface and performance test issues are discussed. Main purpose of the work is reducing testing costs, increase variation of tests and eliminating dependency to ready-to-use products. This system is developed as a part and parcel of the main project called MODEMOF (*MO*tion *D*etection *E*stimation and *MO*deling *F*ramework) which cooperates with another software module developed for the same project. Designed hardware will also be used to design an inertial hardware unit for ETMTS-2 hand-held mine detection system that is developed in TUBITAK (Scientific and Technological Council of Turkey).

Keywords: Inertial Sensing, Motion Detection, Accelerometer, Gyroscope, Bluetooth, IMU, MEMS, Kalman Filter, Degree of Freedom

1. INTRODUCTION

Inertial sensing aims at detecting and measuring acceleration, rotation, motion, tilt, shock and vibration of an object by using inertial systems. Inertial sensing has a wide usage area consisting of industrial, medical, consumer and automotive applications. An inertial system is an inertial sensor package that measures the inertial forces generated by the movement of an attached object.

Early inertial systems were mechanical spinning gyroscopes called as "gimbaled gyro systems". In 1970's, optical ring-laser gyroscopes and fiber optic gyroscopes were invented. In the mid 1990's, MEMS (Micro-Electro Mechanical Systems) for inertial sensor technology showed up and provided reduction in size and costs while increasing performance [6].

IMU devices became popular after the occurrence of MEMS technology in inertial sensor production. IMUs are self sufficient for measuring its own motion. They are small sized packages including a microprocessor, inertial sensors and a communication interface.

IMUs and inertial sensors are used in PGMs (Precision Guide Munitions), INSs (Inertial Navigation Systems), HMDs (Head Mounted Displays), automotive electronics and stabilization of mechanic systems to solve critical problems in practical and efficient ways. GNC (Guidance, Navigation and Control) system of UAVs (Unmanned Aired Vehicle) can be designed with MEMS inertial sensors [4]. IMUs are used in PGMs which are critical to military purposes such as increase in lethality, significantly improve survivability, reduce collateral damage, minimize non-combatant casualties, and decrease the logistics burden or increase the number of kills from the standard logistics load [9]. Designing an HMD with an inertial system can solve various problems that commercially available magnetic, optical, acoustic, and mechanical head-trackers have such as vulnerability to interference, line-of-sight restrictions, jitter, latency, small range, and high cost [2]. Usage of inertial systems in automotive electronics can be seen in crash detection system, vehicle dynamic control system, navigation/driver information system, body/chassis information system [8].

Inertial sensors are also being used in multimedia devices like mobile phones, PDAs and game controllers. A good example for these multimedia devices is the Wii remote controller which is also unofficially known as Wiimote [12]. Wiimote has taken much attention due to having inertial sensors and difference between it and typical gaming controllers. Wiimote has also became attractive because of third party usage of it. There are a lot

of free and open source projects aiming at especially usage of inertial sensors in Wiimote. WiiYourself open source library provides interface to use Wiimote [13]. Wii Homebrew also called as Wiibrew provides various free applications depending on functionalty of Wii remote console [3],[11]. There are also a lot of different virtual reality applications done by using Wii remote controller and these applications achieve the same performance with today's expensive products such as a virtual table [7]. Besides the advantages of developing hardware with IMUs or Wii controllers, there are also disadvantages required to be dealt with. Using end-user hardware packages make designers dependent to characteristics of used packages and increases the cost of tests running with different type of packages.
This paper is about designing a complete motion detection system with configurable hardware, wired and wireless communication hardware and configuration software. Configurable hardware provides usage of plug and play inertial sensor combinations at low cost. Configuration software is used to set runtime characteristics of communication hardware and inertial sensors. With this configurable hardware design, variety of sensor combination and tests to be done with these sensor combinations is increased. Dependency on characteristic of commercial inertial sensor units is eliminated by being able to build up self sensor configuration. The system can be used to design a specific inertial measurement unit with its software for any kind of project in a cost and a time efficient way.

2. SYSTEM DESIGN

The developed system composed of a hardware and a software module. Hardware module includes inertial sensing unit and communication unit. Software module can be considered as two parts which are embedded software running on the device and configuration software running on the user computer.

2.1 Overall System Definition

If detecting a motion is expected to be done with a hand-held small sized device, the device should be power efficient and should be able to collect sufficient data for motion detection. A low power microcontroller should be used for sampling to fulfill the power consumption constraint. However, such a microcontroller would not be fast enough for data collection, filtering, signal processing and data transmission all together. As a result, the device should be a data collector and transmitter but not a data processor. Processing data should run on the computer where the collected data is transferred to. Therefore, hardware design should include a simple microprocessor, a MEMS accelerometer sensor, a MEMS gyroscope sensor, other optional inertial MEMS sensors, and a hardware module designed for communication.

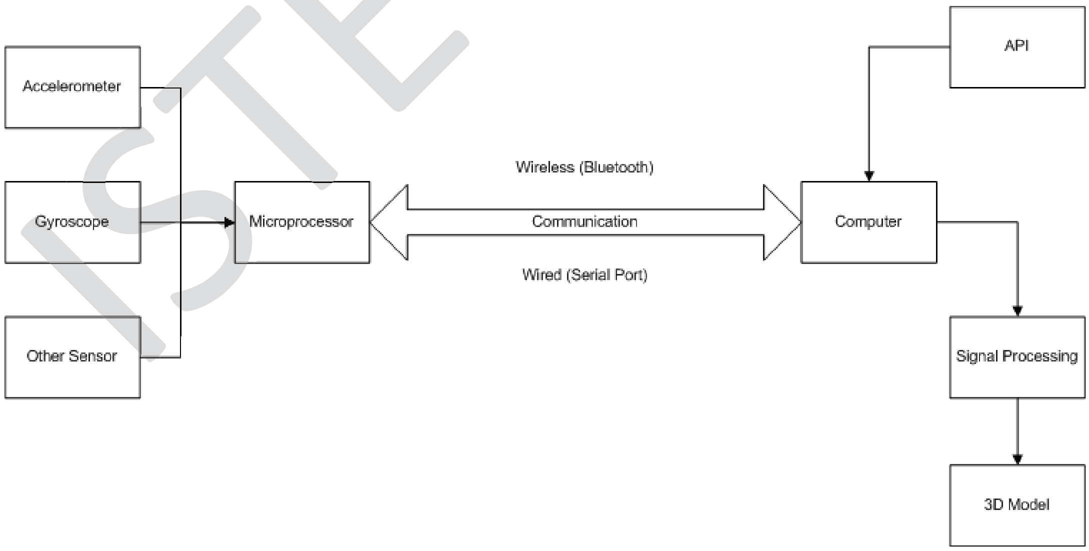

Figure 1: Data flow diagram of a motion detection system using low power hand-held device

Data flow in such a system is visualized in *Figure 1*. Two essential elements of system are a microcontroller/microprocessor and a computer. Data can be transferred between them via wired or wireless communication. Bluetooth is chosen for wireless communication and serial port is chosen for wired communication. The microprocessor controls all inertial sensors and other sensors. An accelerometer and a gyroscope are used for inertial sensing. An API (Application Programming Interface) is used on computer to set all properties of hand-held device such as communication method, communication speed, resolutions for sensors, sensitivity for sensors and active axes of sensors. After setting properties, data transmission from the device to computer starts. Collected data should be filtered and passed to signal processing software. Kalman filters are commonly used in algorithms for motion detection [1] .Processed data can be visualized on a 3D application on the computer.

2.2 Microprocessor and Sensors

A commercial development board (Freescale CSM12C32) which has MC9S12C32 8-bit microprocessor on it is used. MC9S12C32 is fast enough to sample and send sensor data to PC. CSM12C32 provides 40 IO pins which are also enough to externally connect our circuits to the microprocessor. MC9S12C32 has a serial peripheral interface, a serial communication interface and an on chip ADC (Analog – Digital Converter).
Two inertial sensors, an accelerometer and a gyroscope, are decided to be used to design a hand-held device with 6 DOF (degree of freedom). Both of the sensors are used to collect 3-axis data; but they have different communication interface. The accelerometer chosen to be used is “Freescale MMA7455L” MEMS sensor. MMA7455L is a digital 3-axis sensor and has SPI communication interface for setup and data sampling processes. Due to the high cost of 3-axis gyroscopes, two gyroscopes are used to have data for 3-axis. These gyroscopes are IDG-650 2-axis MEMS sensor and ISZ-650 single axis MEMS sensor. IDG-650 provides analog data for X and Y axes. ISZ-650 provides analog data only for Z axis. Positioning of gyroscopes becomes important because of using two sensors to sample data for three axes.
Since the purpose of the hardware is providing a development and test environment, its design has to be easy for plug and play. Besides, different sensor connections and working environments should be realized to provide sample designs for further tests. Therefore, a 3-axis digital accelerometer is chosen to show how to use compact sensor package with digital sensor interface. A 2-axis plus single axis analog gyroscopes are chosen to show usage of analog sensor interface with merging different sensors. So, all four cases (analog interface, digital interface, 3-axis complete package and merging sensors with different axes) that can be faced during design and test are considered.
MMA7455L has I2C and SPI digital communication interfaces; but MC9S12C32 supports only SPI interface. Because of that, SPI interface is used to control the accelerometer.
MC9S12C32 has an embedded ADC. Gyroscopes that are used in the system, namely IDG-650 and ISZ-650, are supposed to be connected to the system via the ADC of the microprocessor. Placement of sensors is critical since we are trying to make two sensors act as one. Two gyroscopes should be placed vertically one above the other with overlapping X-Y axes for correct measurement.
Since we aimed to design a modular system, the hardware should not be compact and all components shouldn’t be in one circuit. All sensors are supposed to have their own circuits. Sensor circuits will be connected to microprocessor via IO pins provided on development board. Any sensor combination can be tested by connecting the development board with any chosen sensor circuits. Since the connections between sensor circuits and development board will be made with cables, characteristics of cables are important. Used cables should not lower voltage value generated by sensor circuits and should not cause noise.
Although the system architecture is configurable, there are still some restrictions have to be considered. The number of analog sensors that can be used is limited by the number of channels on ADC. Digital sensors are driven via SPI. In our SPI connection design, sensors are considered as slaves and the microprocessor is the master. When using multiple slaves in a SPI connection, CS (chip select) pin connections are required to select a slave to communicate. Each SPI bus on a microprocessor provides only one CS pin. Thus, GPIO pins must be used to realize remaining CS pins. As a result, the number of digital sensors that can be added is limited by the number of GPIO pins on the microprocessor.
The design includes accelerometer and gyroscope sensors but any other digital or analog sensors for motion detection, such as a magnetometer, can be added to system by considering the mentioned restrictions. All used inertial sensors should be as close as possible to each other and vertically one above the other.

2.3 Communication

Communication with computers is designed to support both wired and wireless. SCI is used for wired connection and Bluetooth is used for wireless connection. The device is expected to move in 3D space in any direction and to any distance. Using wired communication limits operator’s movement abilities and range. So, wireless communication decided to be added to the system to give user movement flexibility. Bluetooth is chosen for wireless communication among many other options. Note that, using other wireless communication techniques

such as ZigBee requires hardware to be connected on both ends of communication. But Bluetooth has become embedded in almost all computers or small Bluetooth USB devices can be acquired easily nowadays. On the other hand, Bluetooth does not need line of sight availability like infrared communications do. By considering this, our hardware can work with any computer anywhere. Otherwise, making a paired communication hardware to work on and to be compatible with any type of PC would be likely impossible. The aim to make the hardware "plug and play" would fail with other communication techniques. Another advantage of Bluetooth is providing high data rate communication. For further developments on the hardware such as adding image sensor will increase the data that is supposed to be send per second and Bluetooth will be able to meet this requirement.
A commercial Bluetooth module "BlueRadios BR-SC40A" is used for Bluetooth hardware. BR-SC40A is a Class1 Bluetooth® Low Power 18 pin DIP wireless communication serial radio modem module certified to Bluetooth v2.0 with size 20.3(W) X 31.8(L) X 5.0(H)mm. BR-SC40A provides serial communication interface and AT command set to interact with connected hardware. CSM12C32 has a female serial port connector and a RS-232 transceiver protecting the microprocessor. A circuit has to be designed to place BR-SC40A on for establishing communication between CSM12C32 and BR-SC40A via SCI. The circuit must include RS-232 transceiver and male serial port connector. Serial port cables used to connect PC with our hardware also has male connectors. Any serial port cable and the Bluetooth circuit can be connected in the same way.
For the applications that would not use Bluetooth communication, a serial port (SCI) communication is also realized. There is no change required in embedded software to use different communication techniques (*Figure 2* and *Figure 3*)

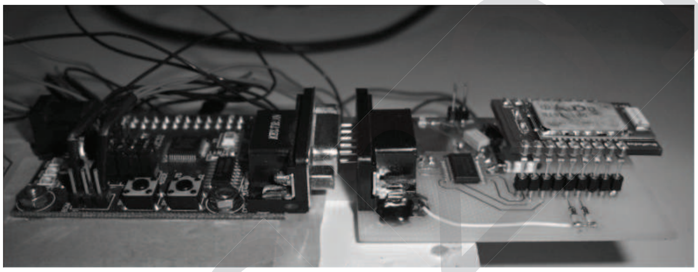

Figure 2: Connecting Bluetooth Circuit (right side) to CSM12C32 (left side)

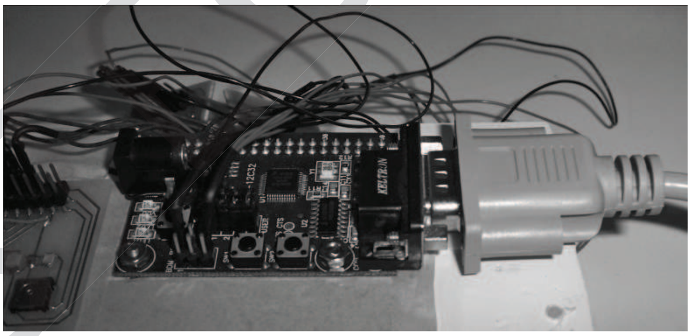

Figure 3: Connecting Serial Port Cable to CSM12C32

2.4 Hardware Configuration Software

Since CSM12C32 recieves all data through SCI interface the active communication method does not make any difference. However, the communication method has to be explicitly mentioned for the software running on PC. A user interface program to select communication interface and to set the properties of the hardware is designed to run on the PC where the data will be recieved and processed. Configurable properties of the hardware can be seen in *Figure 4*.

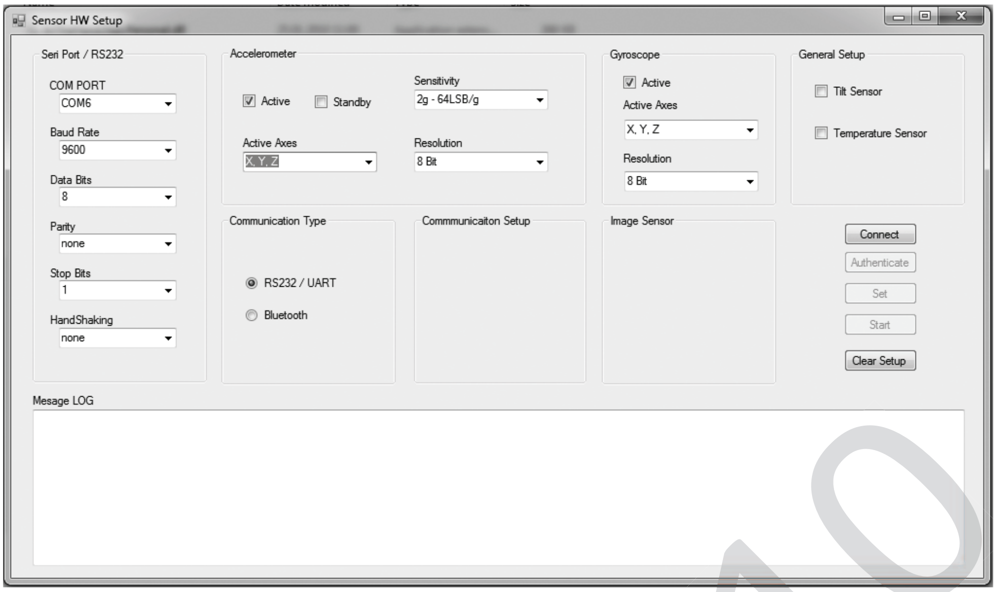

Figure 4: A Snapshot of the Hardware Configuration Software

The user interface program is written with C#. A shared-source C++ library project called 32feet.NET is used for bluetooth connection software of the GUI [5]. Since the designed hardware should be selected among all detected bluetooth devices a pre-set name has to be given for the bluetooth hardware. This is done with using AT command set by embedded software running on the microprocessor. The bluetooth hardware on embedded side has to be in slave mode and waiting for a connection after start up. Slave mode is also set by AT command set. If a connection occurs in slave mode, bluetooth modules enters “fast data mode”. Fast data mode sends every recieved data via SCI to the connected master device.
Regardless of the selected communication technique, the hardware has to be in slave mode and wait for a connection. After detecting a connection, the embedded software expects a authentication code. When authentication is done, a data package for sensor setup has to be send. For last step, embedded software expexcts “START” command string. This structure is built to interact the API with signal processing software. Then embedded software starts collecting and sending data via SCI. If a serial port cable is connected, data is sent to serial port of the master device. If a bluetooth hardware is connected, data is recieved by the bluetooth module and sent directly to the connected master device.

3. CONCLUSION AND FUTURE WORK

In this paper, design of an inertial measurement system was presented. All types of usage of inertial sensors are shown. Methods for wired and wireless communication were given. As a result, a fully expandable and configurable hand-held inertial measurement hardware designed.
The design can be improved in several ways. Number of digital sensors to be connected can be increased by using I2C instead of SPI. This requires selecting a new microcontroller. Also, GPIO pins will not be wasted in this way. Using an external ADC with more channels and better resolution will increase performance and efficiency of analog sensors.
Other sensors such as magnetometer or an image sensor can be added to system to increase motion measurement performance. Improving system characteristics and increasing number of components inside will require higher data transmission rate. One of the main purposes about selecting Bluetooth as wireless communication interface was meeting that requirement. Other purpose was providing an easy usage of the hardware with any computer by using advantage of prevalence in everyday life.
The designed system will be used to emulate motion estimation hardware unit of ETMTS-2 (“Elde Taşınabilir Mayın Tespit Sistemi-2” (“Hand-Held Mine Detection System-2”)) which is developed by TUBITAK UEKAE in Turkey. It is also called as SEZER [10]. ETMTS-2 is a dual sensor mine detection system including EMI (Electromagnetic Induction) and GPR (Ground Penetrating Radar) sensors. Motion estimation will help increasing the performance of signal processing algorithms on GPR sensor data. Another usage of motion estimation in ETMTS-2 will be warning operator in case of not using mine detection system in scanning speed and direction constraints.

4. REFERENCES

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