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Real-time Control System for Various Applications using Sensor Fusion Algorithm

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***Abstract*—Real-time control and monitoring systems uses sensors (accelerometers and gyroscopes), that can be applied to design inertial mouse, object tracking, motion sensing, stabilization and other systems. In order to acquire high system accuracy, most of the implementations demands huge real-time computing. Therefore, the prototype of real-time control system was designed using sensor fusion algorithm that ensures accurate various systems controls with minimal computing resources. Accelerometer data read and accelerometer with gyroscope fusion algorithm results were compared and simple 3D visualization was presented to verify and visually demonstrate the efficiency of proposed real-time control system prototype.**

***Index Terms*—Real time systems, accelerometers, gyroscopes, control system analysis.**

I. INTRODUCTION

In modern society gyroscopes, accelerometers and magnetometers are dominant sensors in consumer electronics. User interfaces, augmented reality, image stabilization, handsets, gaming and pointing devices, motion sensing, medical and industrial instrumentation, orientation estimation systems [1], [2], hard disk drive protection and other applications are based on these sensors (Fig. 1).

Fig. 1. Typical applications.

Some of the implementations on hand detection (motion) and tracking techniques are based on image recognition [3]–[7], to ensure effective real-time interface with robots. However, this method has lots of problems: firstly, because of the lighting conditions, secondly, there is a huge demand of real time computing because of the chaotic and various environment backgrounds and, lastly, the complexity of hand, that has more than 20 degrees of freedom and the more degrees of freedom we have the more computing resources we need.

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II. RELATED WORK

Inertial measurement units (IMU) also are gaining popularity in body motion monitoring [1], robot navigation systems [3] and tracking techniques. Micro-electromechanical accelerometers and gyroscopes are used for these purposes, however, they still present several undesired characteristics in their output that should be compensated through proper device calibration [4]. Calibration of the separate sensors is not sufficient, because the influence of noise is not compensated enough and this is critical to the systems. In order to obtain optimum sensitivities of all sensors were presented in [6] work, but the solution demands huge computing resources, therefore, the latency of the systems performance increases. Other implementation use 12 accelerometers to acquire better accuracy [5], but the systems reliability decreases, when we use many devices, therefore, redundant accelerometers are not as effective as using the array of different sensors, for instance, gyroscope with accelerometer, magnetometer or GPS for better position accuracy estimation. To sum it up, if the sensors are used in separate way, it is complicated to obtain high accuracy in the system. Only by combining data of the sensors it is possible to develop high precision and quick response devices. Therefore, the objective of the paper is to design efficient prototype of real-time control system using sensor fusion algorithm.

III. SELECTION OF HARDWARE: MICROCONTROLLER AND MICRO-ELECTROMECHANICAL SENSORS

For real-time control system prototype Arduino microcontroller was selected, which is an open-source prototyping platform, a tool that is designed for developing interactive objects, taking inputs from the variety of switches or sensors, in order to control lights, servos, motors and other actuators (Fig. 2).

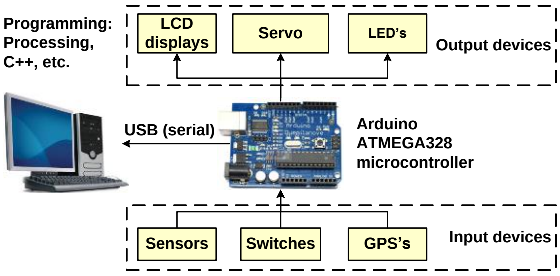

Fig. 2. Arduino prototyping platform application example.

Arduino can operate autonomously or communicate with other software on computer, for instance, Flash, Blender, MaxMSP or Processing. Arduino port specification: 14 digital 5 V tolerant I/O pins with 40 mA DC current per I/O (6 of them PWM outputs), 6 analogue inputs.

Nowadays various sensors are designed to enable selectable sensitivity, for instance, 1.5 g, 2 g, 4 g, etc. The capability to choose multi-axis sensitivities is critical to detect single/double tap, activity/inactivity, free-fall, motion, tilt, shock and vibration for multiple portable applications and functions. Therefore, in order to design real-time control system prototype, the digital 3-axis ADXL345 accelerometer was selected that uses low power, high resolution (13 bit) measurement modes from ±2 g at up to ±16 g, 16 bit digital output data of every axis is accessible through either a SPI or I^2C digital interfaces. The digital 3-axis ITG-3200 gyroscope angular rate sensor with a sensitivity of 14 LSBs per degrees/sec and a full-scale range of ±2000 degrees/sec was also selected. Low power sensor modes enable intelligent motion-based power management.

All the selected sensors are digital, which means that digital logic capable of converting the analogue signal coming from the mechanical components into digital values accessible using a digital communication protocols, in our case, I^2C a 2-wire interface comprised of the signal serial data (SDA) and serial clock (SCL). Moreover, sensors have different configurable parameters, which change how it works internally, for example, configurable sampling rate as well as configurable interrupt conditions. By connecting 2 breakout boards of the accelerometer ADXL345 and gyroscope ITG-3200 on the same I^2C bus in parallel to both SDA and SCL lines, which are open drain and bidirectional, it is possible to design the 6 degrees of measurement system, with the speed up to 400 KHz. It is important to note, that every sensor has its own unique address, for instance, accelerometer has 0x53h and gyroscope – 0x69h. It is also essential to indicate the appropriate addresses sequence for reading or writing data of single, multiple-byte from or to registers, firstly, referring to device address, secondly, to register address. In order to acquire 1-axis data it is necessary to read 2 bytes from 2 different device register addresses.

IV. SENSOR FUSION ALGORITHM FOR RELIABLE AND ACCURATE ORIENTATION SENSING

Using an accelerometer for tilt sensing is simple, however, calculating tilt using only an accelerometer has some limitations. If the user moves the device rapidly or if the device is being used in a vibrating environment, for instance, in a car or a plane, the computed pitch and roll angle values will be completely wrong and unreliable, because sensor suffers from external accelerations and vibrations, which cause errors. Averaging accelerometer readings could be a solution, but only with the assumption that the device is almost steady. In section 2 we described the selected hardware and communication between devices that were used in real-time control system prototype. Therefore, simple, yet efficient self-explanatory algorithm of sensor data fusion (accelerometer and gyroscope) is presented in Fig. 3.

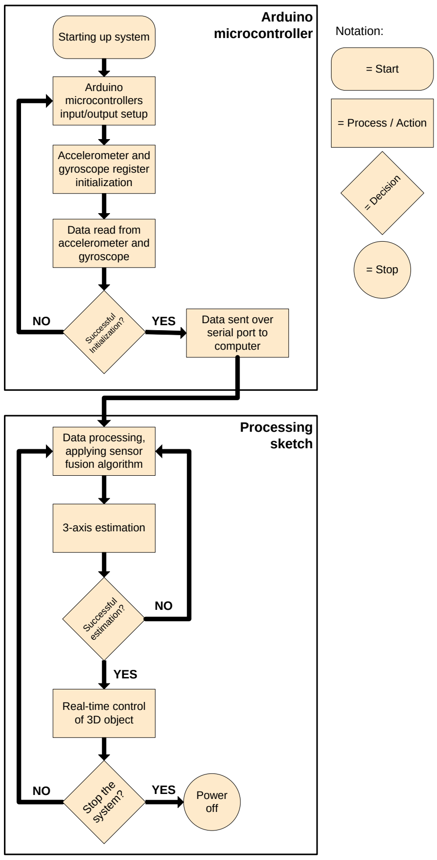

Fig. 3. Sensor fusion algorithm.

After the power up of Arduino microcontroller, the input/output setup, accelerometer and gyroscope register initialization processes takes place, which verifies continuous sensor communication. As mentioned in previous section, sensors are connected to I^2C interface, where SDA channel is responsible for data transmission and SCL for addressing. Furthermore, because there are 2 connected devices on the same I^2C interface, every sensor must have its own unique device address, also different register addresses are required to determine measurement modes, speed of the data gathering, sensitivity, etc. Accelerometer initialization modes starts from powering up sensor, then enabling autosleep functionality, that switches to sleep mode if the inactivity function is enabled and measurement mode, where data read is set to ±2 g, 10 bit resolution and gyroscopes data read is set to 1 sample/read every 8 ms (125 Hz), full-scale range +/-2000 degrees/second and low pass filter is 5Hz. After the initialization processes are verified, sensors proceeds to two parallel raw data read processes of gyroscope and accelerometer. All the data read of x, y, z axis with Arduino microcontroller is then sent over serial port to Processing programming language (Processing sketch) on computer for data processing, where sensor fusion algorithm is applied (combined data) for accurate control, otherwise, if the data read of a single axis from the sensor is unsuccessful (all values does not change or equal to zero) the processes starts from the beginning. The model of real-time control system prototype is presented in Fig. 4.

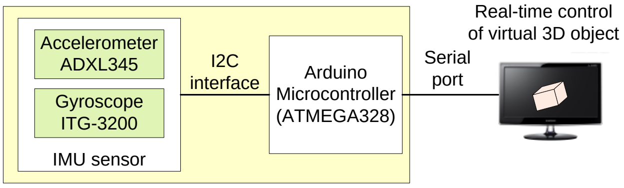

Fig. 4. Model of real-time control system prototype.

The prototype of real-time control system was designed and visualization of virtual 3D object was implemented using Processing programming language, in order to estimate effectiveness of proposed solution (Fig. 5).

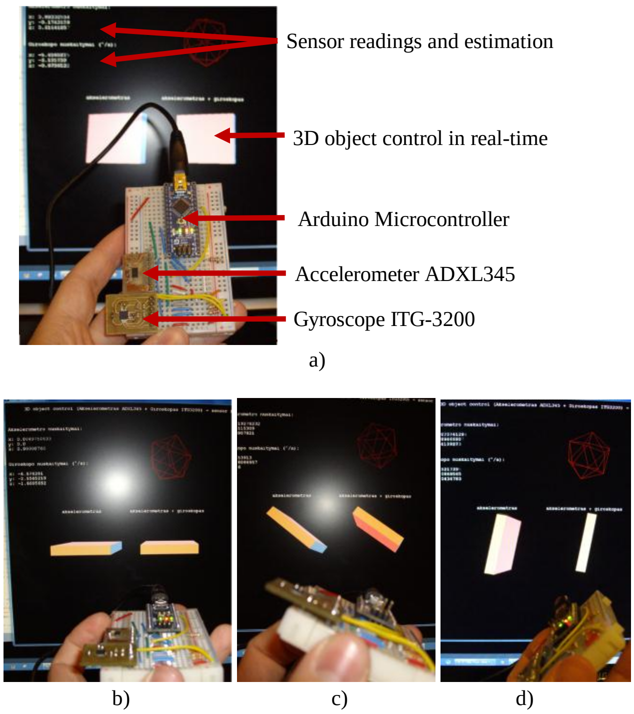

Fig. 5. Prototype (a) of real-time remote control system and visualization of virtual 3D objects; real-time control of 3D object: (b) – horizontal state; (c) – x-axis roll to the right; (d) – x-axis roll to the left.

The left 3D object is controlled only with accelerometer and the right one for smooth control with accelerometer data combined with gyroscopes data (gyroscope compensates accelerometers errors). Before the control (rotation) of the 3D object, the coordinates of accelerometer and gyroscope are estimated and if at least 1 axis is not a number (NaN), the process returns to data processing (according to Fig. 3), because of the wrong data transmission over the serial port. Otherwise, the loop repeats and depending on feedback of the sensors acceleration and angular rate, virtual 3D object is controlled. Moving gyroscope and accelerometer sensors in your hand and depending from the acceleration and orientation, the virtual object moves smoothly in that direction. Such prototype of real-time control system using sensor fusion algorithm can be applied for various applications.

V. Results

In order to verify the effectiveness of sensor fusion algorithm for prototype of real-time control system, the data were analyzed and the following experiments were performed:

1) *Sensor board in stable state;*
2) *Sensor board tilting without vibrations;*
3) *Sensor board tilting applying vibrations by tapping it.*

Sensors output of 1-axis data of the accelerometer and combined accelerometer with gyroscope via serial port are presented in Fig. 6.

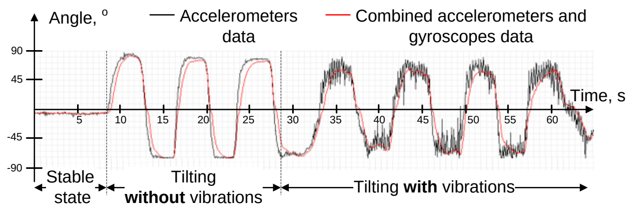

Fig. 6. Experiment results of 1-axis.

The sensors data output of other 2 axis would be analogical. As the experiment results demonstrate, acquiring data from only one accelerometer is not reliable because of these reasons: accelerometer measures inertial force and in ideal case it is caused only by gravity and devices acceleration. Therefore, even if accelerometer is in stable state, it is affected, in general, by mechanical noise (Fig. 6 black line). The gyroscope is also subject to noise and suffers from drift, when not coming back to zero-rate (0 g) value after rotation stops. However, since gyroscope measures rotation it is less sensitive to linear mechanical movements, as a result, gyroscope compensates accelerometer errors. Signal of the combined accelerometer and gyroscope data (Fig. 6 red line) is more immune to noise, than the accelerometer readings alone of every axis. Nevertheless, by averaging and combining accelerometers and gyroscopes data it is possible to obtain accurate data estimation for real-time control system, than we would obtain using sensors separately.

VI. Conclusions

The research indicates that the proposed system suggests efficient real-time control system prototype. The biggest advantage of the designed system is its wide range of application capabilities in various fields, for instance, the use of IMU inertial sensor in real-time control system for new generation inertial mouse, using single/double tap capabilities of the ADXL345 accelerometer it is possible to design a mouse that would require no buttons, where buttons are replaced by taps and menu scrolling by orientation; also, it can be used for an unmanned aerial vehicle for stabilization and tracking during flight, augmented reality technology, to manipulate the elements of 3D model, developing prototypes of human computer interaction devices, tangible user interfaces, in general, for accurate control of technical-systemic platforms. 3-axis data read from the sensors (3-axis accelerometer and 3-axis gyroscope) were implemented and sensor fusion algorithm applied for the prototype of real-time control system. The experiment results were compared and demonstrate, that the data read from one sensor is not sufficient, therefore, the array of sensors with 6 degrees of freedom were used. Furthermore, the visualization of 3D virtual object was implemented using Processing programming language, in order to visually estimate the effectiveness, increased sensitivity and reliability of the orientation sensing capabilities of the proposed solution. Accordingly, the measured data of linear acceleration, gravity and orientation were used in sensor fusion algorithm to get minimal biases, while controlling the orientation of virtual 3D object.

In further development process the magnetometer HMC5883 and wireless ZigBee module will be added in order to design more accurate real-time remote control system over wireless long range communication or wireless close range communication with computer via Bluetooth. Depending on the task it is possible to use other sensor capabilities, for instance, temperature measurements with gyroscope or free-fall, activity and inactivity detection with accelerometer, altogether designing tangible user interfaces.

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