Wireless 3-Axis Accelerometer System for Measurement of Structural Displacement

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Abstract

In this study, we present the design of a 3-axis acceleration measurement system that is capable of UTC (Coordinated Universal Time) time-stamping captured from a Global Positioning System (GPS) receiver module. With this achievement, the system is able to monitor and record the 3-axis vibrations with respect to an absolute time rather than the local sensor (and computer) time. Acquired 3-axis acceleration data and UTC are transferred via Bluetooth® protocol and developed software which enables monitoring and recording of UTC and acceleration data on a PC, respectively. For verification and synchronization quality test of acceleration data, shake-table tests were conducted for simulation of structural displacement and the calculated displacements were compared with a displacement sensor of a commercially available shake table system.

1. Introduction

As the building practices improve by the development of the construction techniques, there is a need to endorse the principles of the structural design philosophy. The recent developments in the data acquisition systems such as accelerometers, inclinometers provide a basis to measure the response of the existing structures such as buildings, bridges under several loading conditions [1-4]. Among these acquisition systems, the conventional linear variable differential transformers (LVDTs) are practically cumbersome to install and operate since they require reference and observing parts for direct displacement measurement [5, 6]. However, a single accelerometer could measure even the multi-axis relative displacement after applying double integration. On the other hand, wide sensor nodes of the accelerometers should be installed on all over the engineering structures in order to monitor the system response for real time dynamic excitations such as wind, earthquakes etc. Such an approach causes a challenge of processing of the data from the sensors simultaneously. The network latency due to spatial distribution of the sensors in addition to different sampling rates of the sensors introduces uncorrelated data acquisitions. In order to avoid the timing correlation of the data from various sensors, there is a need to synchronize the data sample timing according to a common reference. In the literature, there exist several approaches to handle the synchronization problem [7-11]. In this study, the reference timing of the data acquisition is captured from the clock of a commercial low-cost GPS receiver module which is accurate with atomic clock in nanoseconds precision.

2. System design and realization

The accelerometer system consists of hardware and software components. The hardware acquires both acceleration signals and UTC time and then transmits these using Bluetooth® protocol. The software enables the realtime monitoring, recording and interpretation of acceleration data.

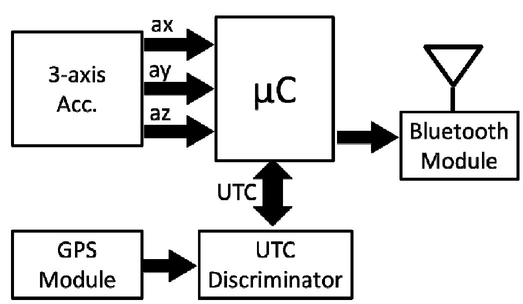

Fig. 1. Block diagram of designed hardware

2.1. Hardware

In the hardware part, PIC16F877A 8-bit microcontroller [12] handles the acquisition of accelerometer data, captures UTC time using an additional discriminator connected to the GPS receiver module and merges these data for transmission via Bluetooth® module. To communicate with these modules, the microcontroller uses I2C® communication protocol for accelerometer module and UART interface for GPS and Bluetooth® modules, respectively. Microcontroller program codes were written and compiled with Proton IDE software.

To enable 3-axis acquisition of acceleration data, LSM303DLH 3-axis accelerometer module [13] was used. The dynamic range of this module can manually be adjusted to ±2, ±4 or ±8 g, respectively. The acquisition frequency was optimized at 110 Hz sampling rate to get 12 bit ADC data.

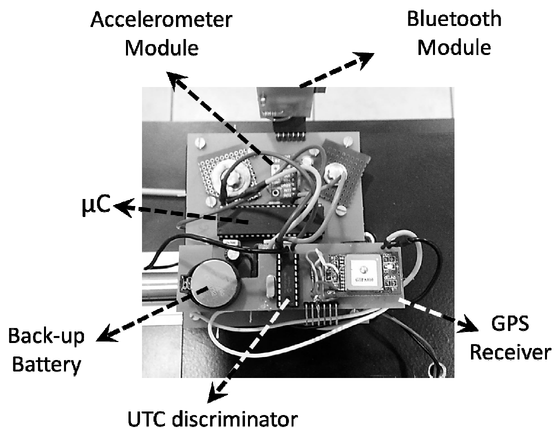

Fig. 2. Top view of the realized hardware

The chosen GPS receiver module (MediaTek - MT3329 [14]) has a maximum capacity of 66 channels in L1 band. In the test process of the GPS receiver module, the baudrate of UART communication was pre-adjusted to 57600 bits per second (bps) with a refresh rate of 1 Hz, only to send the string $GPRMC which is common in National Marine Electronics Association (NMEA) sentences.

UTC discriminator checks whether any new data is available from GPS receiver module and extracts the concurrent UTC time from the incoming sentence starting with $GPRMC. The Bluetooth® module HC-06 [15] realizes wireless transmission of data at a baudrate of 57600 bps. The digital accelerometer data and UTC time are transmitted in the string array form as

XFF0F**Y**001E**Z**EF00**123456**<cr><lf> (1)

where “cr” stands for “carriage return” and “lf” stands for “line feed” character, respectively. The system is powered with a 9V battery and consumes approximately 1 W. A back-up battery of 3V is also included in the system to keep GPS on-board clock power on and retain module settings.

Table 1. String format for data text file

assigned row #	computer seconds	Acc. x-axis	Acc. y-axis	Acc. z-axis	UTC Time
1	24	0.018	-0.055	-0.973	100123
2	24	0.026	-0.028	-0.975	100123
…	…	…	…	…	…

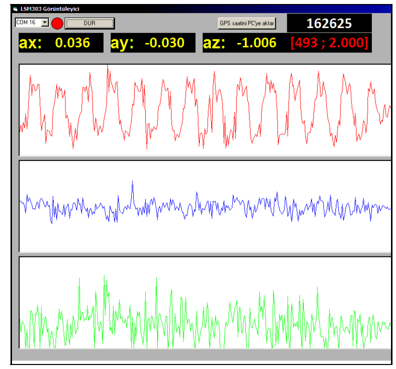

Fig. 3. Software screen: ax, ay and az denote the 3-axis directions and the numerical values are monitored simultaneously in “g” units. UTC time (16:26:25) is shown in top right hand side

2.2. Software

The Microsoft Windows® execution file (.exe) of the system’s software is compiled using Microsoft Visual BASIC®. The software first sets one of the available visual serial communication ports (or COM ports) for Bluetooth® communication. The synchronization of UTC wall clock and local computer clock is updated in only MM:SS (minute and seconds) format with the “Sync” button since there exists an hour difference between UTC and local time (for Istanbul, Türkiye). As soon as the first data is received, a new “text” file (.txt) is generated with respect to concurrent computer date and time. The data stream, consisting of 3-axis floating acceleration data, an assigned row number (with modulus 255), computer seconds and concurrent UTC time are acquired in the form as shown in Table 1.

The 3-axis accelerometer data and UTC time are instantaneously monitored in roll mode on PC screen which is cleared in every 500 samples (Fig. 3).

3. Experiments

Several experiments were conducted to mainly test the performance of a) structural displacement calculation and b) UTC time synchronization of acquisition.

In order to have a specific and controllable displacement change, we have used an electro-mechanical shake table (TestBox® Shake Table - Teknik Destek Grubu, Türkiye) that is controlled by a digital servo controller and acquisition unit (Control Box® - Teknik Destek Grubu, Türkiye) and its software. Shake pattern is chosen to be a simple sinusoidal movement with a specific peak displacement and a specific oscillation frequency. Using Control Box® unit, exact displacement changes can be recorded using built-in LVDT displacement sensor of the servo controller.

3.1. Inspection of accelerometer offset

The offset in accelerometer data leads incorrect results in calculation of displacement. Since the accelerometer’s motion plane was not perfectly horizontal, acquired accelerometer data had an offset at a specific level. To reveal the offset clearly, idle mode (no movement) data were acquired and analyzed (Fig 4, 5). Note that the large offset in *z* component is due to earth's gravity.

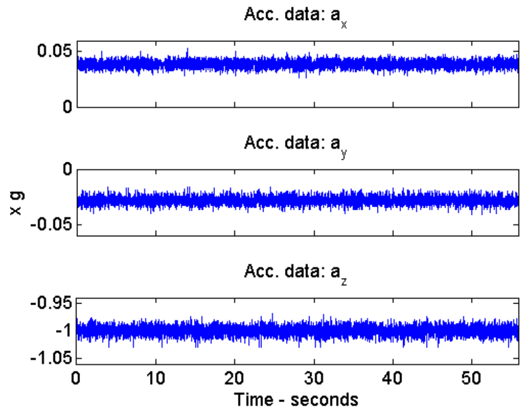

Fig. 4. Samples of 3-axis, 60 seconds (6,6K samples) acceleration recording in idle mode

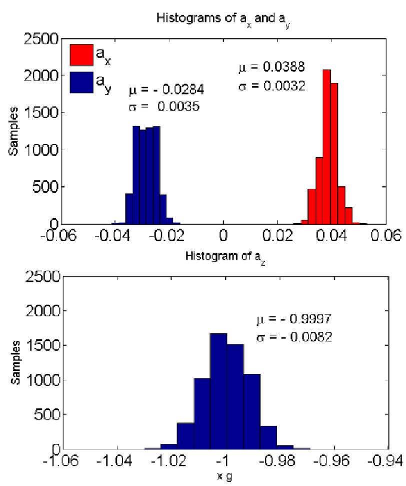

Fig. 5. Histograms of acceleration data of Fig.4

3.2. Verification of calculated displacement

The total displacement calculations were compared with LVDT output of Control Box® unit. As an offline process, double integrations of 3-axis accelerometer data in only x-direction were calculated. For offline comparison, reference LVDT values were extracted from recorded data file of Control Box® unit.

Two methods of calculating the displacements from the measured acceleration are possible: a) removing the noise from the acceleration measurement data with a band-pass filter (BPF) and applying double integration, or b) using the central differencing scheme and the Tikhonov regularization scheme without additional filtering [6]. As shown in Fig.4, the acquired acceleration data involves a constant offset. The relevant offset, if not eliminated, causes a constant trend change when integrated. In addition, high frequency noise that can be seen in idle mode raw data (Fig.4) causes random drifts or namely "random walk" after integration. Thus, incorrect velocity and displacement values will be obtained for unfiltered (raw) acceleration data. To handle this problem, we applied 2[nd] order Butterworth type BPF to acceleration data.

The offset removed raw and filtered x-axis accelerometer data that were acquired during 2Hz – 60 mm peak sinusoidal movement of shake table is shown in Fig. 6.

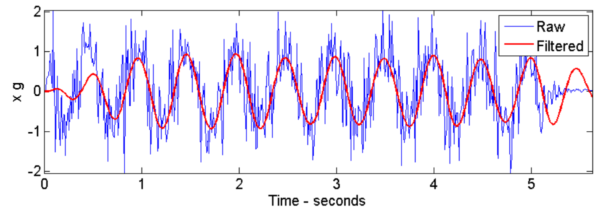

Fig. 6. Unbiased and filtered x-axis acceleration data for 2 Hz, 60mm peak sinusoidal movement

After filtering of raw acceleration data, to calculate displacement, double integration was applied. The calculated displacement and reference LVDT comparison is shown in Fig.7.

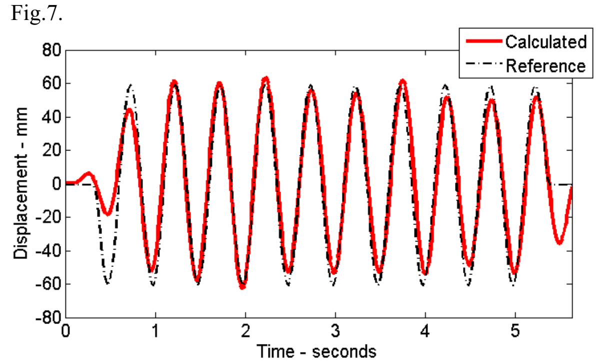

Fig. 7. Reference and calculated displacement values for 2 Hz, 60mm peak sinusoidal movement

3.3. Verification of UTC time synchronization

In order to test the synchronization of UTC time with acquired computer seconds (Table 1), corresponding columns are extracted from text file by offline processing. As shown in Table 1, column 2 and 6 includes the computer seconds and UTC time (in HH:MM:SS format), respectively.

The direct way to determine the performance of synchronization is to check whether the computer time (seconds) and UTC time are the same. Note that even if a specific "second" row of acquisition data is same for both computer and UTC seconds, they may have different time-lag in millisecond precision. This difference has to be kept as small as possible by the acquisition system. In addition, the relevant time-lag should be constant through very long periods (days, months, etc.) of acquisition. Even a millisecond time-lag shift may lead to a total time difference of seconds and minutes during these very long observation periods. This is the main problem in wide sensor node networks as stated earlier.

Referring to above mentioned reasons, we have checked time-lag between computer and UTC seconds in sample wise (Fig. 8, Fig. 9). As a further check, we have calculated time-lag in every hour of a 24 hour data acquisition (Fig. 10).

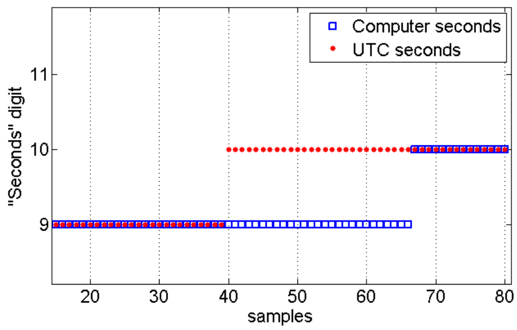

Fig. 8. Initial time-lag between computer time and UTC time in sample wise. Considering origin as 40th sample, the time-lag can be seen to be 27 samples

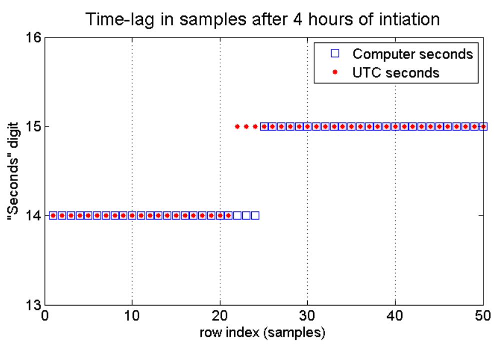

Fig. 9. Time-lag in samples after 4 hours of initiation. The lag between computer and UTC seconds are still small as 3 samples

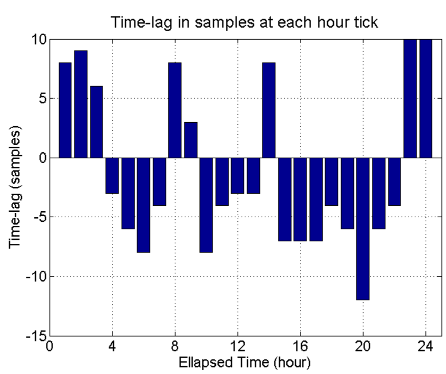

Fig. 10. Time-lag in samples vs. elapsed acquisition time (in hour). Note that the probing for time-lag measurement was sampled only in hour ticks

4. Conclusions

In this study, we have developed a low-cost 3-axis accelerometer system that enables wireless transmission of acceleration data accompanied with well referenced occurrence times. By using the acceleration data acquired through the shake table tests for simulating structural displacement, we managed to precisely calculate the known displacement using acceleration data. In addition to correct displacement measurements, we were also able to acquire UTC timing in a precision less than 100 milliseconds through a 24h acquisition period.

5. References

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