Experimental Study of Low Cost Multiple IMU Based Open-source Motion Sensing Platform for Data Logging in Seismic Shaking Table Test

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Abstract**:** ***Micro-electro-mechanical systems (MEMS) based inertial measurements units (IMUs) have become very popular in recent times because of low cost, small size and non-invasive nature. One of the major domains of its use is design of wearable sensors for human motion sensing and analysis. As a result, number of open-source motion sensing hardware and software platform have come up. This paper presents experimental study of one such open-source wearable motion sensing platform, Oblu, for measuring structural response of models in seismic shaking table test. Required customization of open-source platform to meet needs of data logging in seismic shaking table test is discussed. Also, the details of post-test data processing and analysis done on another open-source platform Scilab is discussed. To compare the results of experimental study, analysis of similar model, subjected to identical test conditions, is performed using Structural Software for Analysis and Design SAP2000. The study shows potential of using low cost open-source motion sensing platform in comparison to expensive and proprietary accelerometer based data logging systems conventionally used for seismic shaking table tests.***

Keywords**: Inertial Measurements Unit, Seismic Shaking Table, Structural Response, Open-source motion sensing platform.**

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I. Introduction

Development of sensing technologies and sensor signal processing methods have opened up new directions for their use in diverse domains. Inertial measurements units (IMUs) are one such example. IMUs are micro-electro-mechanical systems (MEMS) based sensors that are more popularly used in motion tracking research. Being cost-effective, small size, non-invasive and portable, they have proved to be better alternative to conventional optical and mechanical type tracking devices. IMUs are used in a variety of applications such as medical, sports, smartphones but are particularly used in navigation of various platforms such as autonomous under-water vehicles, unmanned ground and aerial vehicles [1-4]. As the scope of applica-tion of IMU has increased, market has witnessed rise of companies that sell IMUs and IMU-based systems.

IMU, typically, is composed to accelerometers and gyroscopes and is used to ob-tain information about acceleration, velocity, position and orientation. However, IMU measurements are not accurate and have considerable errors due to time vary-ing biases and noises. Efforts have been put in by researchers, both in terms of hard-ware modification as well as using algorithmic approach to improve the overall accu-racy in motion sensing [5, 6]. One of the approaches to counteract the problem of drift and thereby improving the accuracy is to use multiple IMU architecture [7]. As IMU are relatively low cost devices, using them in multiplicity does not add much to the overall system cost.

In recent times much work have been done towards IMU based wearable sensors for human motion sensing and analysis. This has also lead to development of num-ber of open-source hardware and software platforms [8-10]. Though these platforms are proposed for human motion sensing, being open-source, they can be conveniently modified, altered and used for other purpose too. Seismic shaking table is one such example. Seismic shaking table is generally the part of Earthquake engineering labor-atory and is used to investigate seismic performance of scaled model of different types of structures and materials. Dynamic characteristics and the responses of the model to different seismic intensities are studied through analysis of shaking table test data and cracking patterns observed. One of the important test data collected during the shaking table test is that of acceleration against time.This paper presents an experimental study of use of a low cost open-source motion sensing platform, along with other open-source platforms for signal conditioning and data processing for the purpose of data logging and analysis in seismic shaking table test. Remaining part of the paper is organized as follows. In section 2, details of open-source motion sensing platform used in the experimental study is discussed. Details of experimental setup and methodology used is discussed in Section 3. This is followed by discussion on results in Section 4 and conclusion in Section 5.

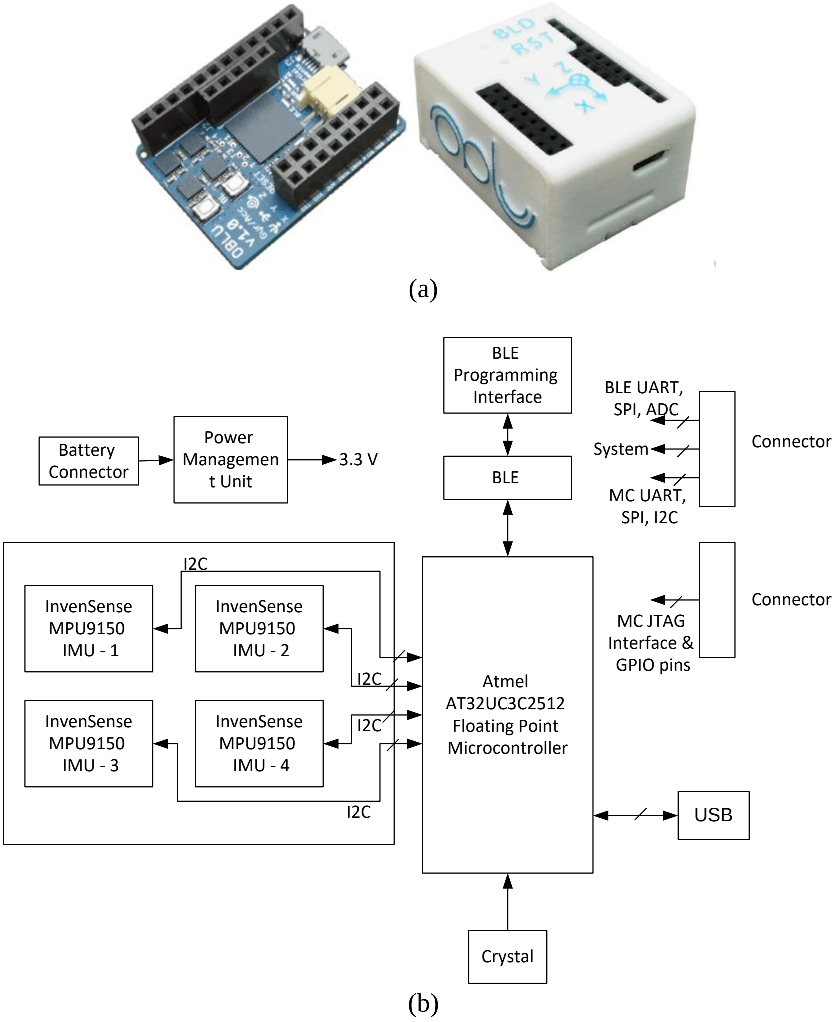


Fig. 1. (a) Oblu development board with and without casing. (b) Oblu block diagram.

II. OBLU – AN OPEN-SOURCE MOTION SENSING PLATFORM

Oblu, is one among various Multiple IMU based open-source motion sensing platforms available. It comes pre-programmed as a wearable sensor for pedestrian navigation. However, with the help of documentation and support available, it can conveniently be customized for other applications [11]. Oblu promises to be a better alternative compared to its peers because of its stability, dynamic range, sampling rate, analog bandwidth and cost. Further, it provides wireless link for data communication, is battery operated and has small foot-print.

A. Hardware Details

Fig. 1(a) describes Oblu development board and Figure 1(b) describes its block dia-gram. Major features of the development board are listed as follows [11].

- Atmel AT32UC3C2512 32-bit floating point controller operating at 16 MHz.
- Four MPU9150 9-axis IMUs (3-axis Accelerometer + 3-axis Gyroscope + 3-axis magnetometer) from InvenSense.
- Interface through STMicroelectronics Bluetooth Low Energy (BLE) v4.1 and USB2.0.
- Access to UART, SPI, I2C and GPIO pins.
- Programming through USB (Bootloader) and JTAG interface for microcontroller and BLE.
- Power management unit with options of powering from Li-ion battery or USB connector.
- Battery chargeable through USB.
- 4-layer PCB with dimension 22.5 x 20 mm.

MPU-9150 is the 9-axis motion tracking device with on-chip digital motion proces-sor hardware accelerator engine. The scale range and analogue bandwidth of the accelerometers are ±16g and 260 Hz, respectively, and that of gyroscopes is ±2000 °/s and 256 Hz [12]. Placement of IMUs in Oblu development board is in 2 x 2 array. The microcontroller communicates with IMUs over I2C and with Bluetooth module over UART. Individual IMU data can be sampled at maximum 1 KHz. The board operates on 3.3 V and a module casing is available that encloses the PCB and the battery. Overall dimensions of the enclosure is 23.2 x 31 x 13.5 mm.

B. Software Details

Different software components that is part of Oblu motion sensing platform includes [11].

- Microcontroller code that consists of components like runtime framework, communication routines, device drivers and actual zero-velocity aided inertial navigation filtering implementation. The code has been written in C using Atmel Studio 6 IDE.
- BLE firmware that acts as UART-BLE bridge between microcontroller and user interface. It has been written in C using Cypress PSoC Creator 3.1.
- MIMUScope is a Windows/Linux based user interface for Oblu devices. It provides option to select sampling rate and to get raw / processed data with time stamp in both plot and text file form. The application has been developed in Python.

III. Experimental Setup and Methodology

A. Seismic Shaking Table

Uni-axial motorized electro-mechanical shake table was used for the experimentation. The shake table has been designed and developed at Darshan Institute of Engineering & Technology. The advantages of electro-mechanical shake table, compared to hydraulic system, is its low-price and low operation costs which makes it suitable for academic and basic research purpose. Major specifications of the shake table used here are as follows.

- Size 5 ft. x 3 ft. table platform with 12 mm diameter holes at 50 mm distance for fixing model
- Servo motor controlled platform movement
- Programmable Logic Controller (PLC) and Human Machine Interface (HMI) based electronic control panel
- Payload capacity- up to 500 Kg
- Platform movement - Amplitude range 0 to 100 mm, Speed/frequency in terms of harmonic input: up to 6 cycles/second
- Three modes of operation – Harmonic – manually controlled, Harmonic – controlled as per data table and Random motion.

B. Model under Test

The experimental study was performed on a model made from Aluminum having three degrees of freedom. The model consists of a three plate 300 x 150 mm size supported by four 25 x 3 mm thick columns. Columns were fixed with plates using check nuts instead of welding to avoid errors due welding. Experimental setup is shown in Fig. 2

C. Methodology

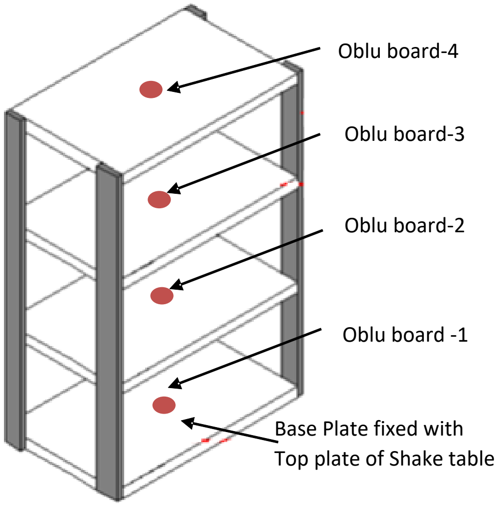
The model was fixed on the platform of shake table which represents structure fixed to the ground. In experimental setup, four Oblu development boards were used as acceleration sensors to get the response of model during shaking. Fig. 4(a) shows mounting arrangement of Oblu development boards. One board was mounted at the center on the bottom plate of the model and is expected to provide input motion value of shake table. Other three boards were mounted at center of plate at each slab level. After setting up model and Oblu boards, tests were performed by applying harmonic motion of different amplitudes and frequencies. For this experiment Oblu boards were configured to give data only of acceleration. Sampling rate used to log the data was of 250 samples per second i.e. samples at interval of 0.004 sec. Data from four Oblu boards were logged in four text files. Logged data from each board contains values of accelerations along x, y and z-directions in m/sec^2 along with time stamping.

Fig. 2. Experimental setup – Seismic shaking table and model under test.

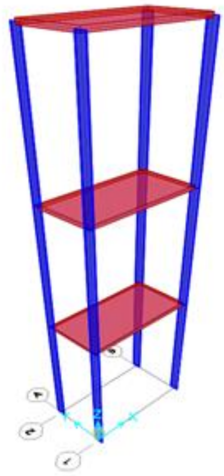
The logged data, thus obtained, is further processed offline using Scilab to remove noise and analyze the data in time and frequency domain. The noise here, primarily represents mechanical and signal noise of the shake table equipment introduced while performing the experiment. Scilab is one of the popular free and open-source platforms for high-level numerical computation. Steps involved in offline processing of logged data are shown in Fig. 3. After importing the data from log files into Scilab environment, the acceleration data is pre-processed which majorly involves filtering operation. Filter used here is fourth order Butterworth bandpass filter. Preprocessing helps to remove noise and possible drift. Processed data is then numerically treated to get the desired information in time and frequency domain. From acceleration, information about velocity and displacement is derived. Further, the data can also be analyzed in frequency domain using Fast Fourier Transform or in time-frequency domain in terms of signal Spectrogram.

Fig. 3 Steps in offline processing of logged data using Scilab

To compare the results obtained through experimental study Structural Software for Analysis and Design SAP2000 was used. Using finite element approach, the model under test was created using SAP2000, and its behavior was analyzed by subjecting it to input waves similar to that used



(a)



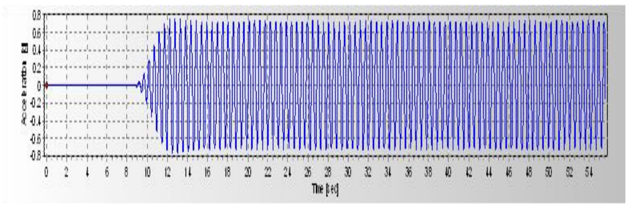
(b)

Fig. 4 (a) Model under test with accelerometer location. (b) Model generated in SAP2000.

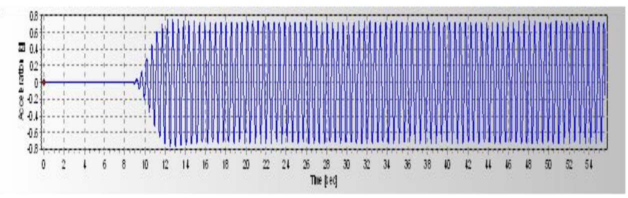
in experimental study. Fig. 4(b) shows model generated in SAP2000.

IV. Results and Discussion

Data captured from different Oblu boards were processed using Scilab and the response of the model was obtained in form of acceleration, velocity and displacement at each storey level. Acceleration measured at different storey levels for typical test condition of harmonic motion with amplitude of ±5 mm and frequency of 2 Hz measured for around 50 seconds is shown in Fig. 5.



(a)



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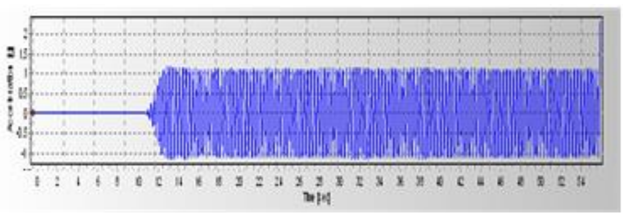

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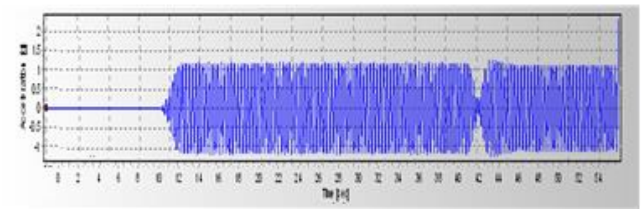

(d)

Fig. 5 (a), (b), (c) and (d) Graph of acceleration versus time at storey level 1, 2, 3 and 4 respectively.

The experimental results thus obtained were compared with those obtained from the analysis of model in SAP2000 and were found to be in agreement within acceptable limits. For the typical test condition mentioned above, Table I describes one of the parameters used in comparison of experimental and analytical results which is maximum acceleration and displacement at different storey levels in the model.

V. Conclusion

A comprehensive experimental study was carried out to investigate performance of low cost open-source motion sensing platform in measuring structural response of models in seismic shaking table test. From among different open-source platform available, Oblu motion sensing platform was used for the experiment. For the purpose of comparison, the structural response of similar model under identical test

TABLE I. Comparison of Experimental and Analytical results.

Location	Max Displacement (mm)			Acceleration (g)		
	Experimental	Analytical	% Difference	Experimental	Analytical	% Difference
Storey-1	5.00	-	-	0.71	-	-
Storey-2	5.23	5.06	3.25	0.74	0.667	9.86
Storey-	7.92	7.23	8.72	1.14	1.065	6.57

3						
Storey-4	8.12	8.64	6.40	1.20	1.29	7.50

conditions was analyzed using Structural Software for Analysis and Design SAP2000. Difference observed in experimental and analytical results are within acceptable limits. The study shows the advantage of using low cost open-source motion sensing platform and data analyzing platform over the expensive and proprietary accelerometer based sensors and software for data analysis in seismic shaking table tests. As per a rough estimate, the proposed setup for experimental analysis of structures on shake table costs around one-fifth of the proprietary solutions available in the market. Encouraged by the results of this study, the authors are working towards development of an open-source data logging system for seismic shaking table.

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