Life-Cycle of Structures and Infrastructure Systems – Biondini & Frangopol (Eds)

A review on low-cost sensors compatible with open-source platforms used for life-cycle monitoring of civil structures

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ABSTRACT: Lately, the need for adopting sensors in buildings and infrastructures for monitoring and inspection of the health state of those structures is increasing. This demand is due to the increasing age of the structural stock worldwide. Consequently, more economical ways of Structural Health Monitoring applications are getting huge attention. This paper presents and evaluates several low-cost electronics compatible with open-source digital technologies for static and dynamic Structural System Identification applications. Firstly, an open-source microcontroller (Arduino), the main programable logic controller, and a Raspberry pi, a small single-board computer, are introduced. Secondly, various economic sensors with diverse measurement applications, such as ultrasonic and laser ranging, acceleration, temperature, and humidity, are discussed. Thirdly, multiple experiments in different controlled ambients are applied to assess and compare their tolerances as well as advantages and disadvantages of their use, among their price. Some problems with the Arduino codes and sensor positions emerged during the installation of the sensors and the data collection process. Finally, to attain an effective manner of using these low-cost electronics, this article offers answers to the issues faced.

1 INTRODUCTION

Lately, the demand for adopting sensors in infrastructures and buildings is increasing. This need is due to the monitoring and inspection of the health state of those structures. Consequently, more economic ways of SHM applications are getting huge attention (Komarizadehasl et al. 2022). In this article, several models of low-cost sensors have been introduced. Furthermore, the features of each one of them have been explained. Each sensor could be applied in a particular circumstance. Every sensor has benefits as well as weaknesses in various conditions. To be able to work with them, firstly Arduino Uno (which is the main programmable logic controller (PLC) in this project), and a Raspberry pi, a small single-board computer, are introduced. Secondly, diverse types of sensors along with their specifications have been introduced. Each type of sensor may use a different way to send its data. Thirdly, different ways of communicating with this PLC will be presented. Finally, the results of these sensors have been illustrated.

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2 STATE OF THE ART

In this section the sensors and a microcontroller that has been used in the project will be reviewed along with their technical descriptions.

2.1 *Arduino Uno*

Arduino is an open-source electronics platform based on easy-to-use hardware and software. Aduino Uno is a microcontroller board based on the ATmega328P. It has 14 digital input/output pins, 6 analog inputs to measure and convert the voltage to a digital value. It facilitates numerous interfaces to communicate with other microcontrollers and computers such as Inter-Integrated Circuit (I2C), Serial Peripheral Interface (SPI) and Universal asynchronous receiver/transmitter (UARTA) (Pathak et al. 2019) (Komarizadehasl et al. 2022) (Mahyad Komary et al. 2023). Figure 1 is the schematic of the Arduino Uno circuit.

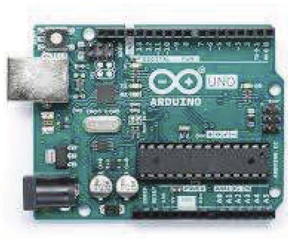

Figure 1. Schematic of the Arduino Uno (Pathak et al. 2019).

2.2 *Raspberry Pi*

Raspberry Pi is a low cost, small and portable size of computer board. It can be used to plug-in to computer monitor or television, keyboard, mouse, pen-drive etc. Raspberry Pi has built in software such as Scratch which enables users to program and design animation, game or interesting video. In addition, programmers can also develop script or program using Python language; it is main core language in Raspbian operating system (Komarizadehasl, Lozano Galant, et al. 2022b).

Figure 2. Schematic of the Raspberry pi.

2.3 *Ultrasonic sensor*

Ultrasonic ranging module HC - SR04 provides 2cm - 400cm non-contact measurement function which on Figure 3 its schematic has been presented. For this sensor, the ranging accuracy can reach to 3mm. The modules have transmitters, receiver and processing circuit. The basic concept of work is: firstly, using I\O trigger for at least 10uS (microsecond) high level signal. Secondly, The Module automatically sends frequency of 40 kHz and detect whether there is a pulse signal back. Finally, the range can be calculated through the time interval between sending trigger signal and receiving echo signal. Test distance = (time × velocity of sound (340M/S)) (Kamal and Hemel 2019).

Figure 3. Schematic of an Ultrasonic ranging module HC-SR04 (Kamal and Hemel 2019).

2.3.1 *Humidity sensor*

As it has been written on section 2.3, for measuring the distance using that sensor the speed of sound is needed. The sound travels in different speeds in different temperatures and humidity (M. Komary et al. 2022). The schematic of this sensor has been shown on Figure 4. DHT22 has already been calibrated during production process and provides accurate information (Patil, Khedkar, and Jadhav 2019) (Liu 2013).

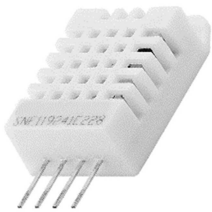

Figure 4. Schematic of a DHT22, digital temperature/humidity sensor.

2.4 *The VL53L1X*

The VL53L1X, which has been shown on Figure 5 is a state-of-the-art, Time-of-Flight (ToF), laser-ranging sensor, enhancing the ST FlightSense™ product family.

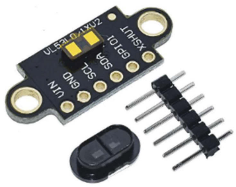

Figure 5. Schematic of a VL53L0X (Adafruit 2018).

It is the fastest miniature ToF sensor on the market with accurate ranging up to 4 m and fast ranging frequency up to 50 Hz Housed in a miniature and reflowable package, it integrates a SPAD receiving array, a 940 nm invisible Class1 laser emitter, physical infrared filters, and optics to achieve the best ranging performance in various ambient lighting conditions with a range of cover window options. Unlike conventional IR sensors, the VL53L1X uses

ST's latest generation ToF technology which allows absolute distance measurement whatever the target color and reflectance. It is also possible to program the size of the ROI on the receiving array, allowing the sensor FoV to be reduced (Adafruit, 2018).

2.5 *MPU 9250*

The MPU-9250, delivered in a 3x3x1mm QFN package, is the world's smallest 9-axis Motion-Tracking device and incorporates the latest InvenSense design innovations, enabling dramatically reduced chip size and power consumption, while at the same time improving performance and cost. The MPU-9250 Motion-Tracking device sets a new benchmark for 9-axis performance with power consumption only 9.3μA and a size that is 44% smaller than the company's first-generation device. Gyro noise performance is 3 times better, and compass full-scale range is over 4 times better than competitive offerings(Mahyad Komary et al. 2022).

The MPU-9250 is a System in Package (SiP) that combines two chips: the MPU-6500, which contains a 3-axis gyroscope, a 3-axis accelerometer, and an onboard Digital Motion Processor™ (DMP™) capable of processing complex Motion-Fusion algorithms; and the AK8963, the market leading 3-axis digital compass (Komarizadehasl et al. 2022). Improvements include supporting the accelerometer low power mode with as little as 6.4μA of and it provides improved compass data resolution of 16-bits (0.15 μT per LSB) (InvenSense 2014). On Figure 6 schematic of this sensor can be seen.

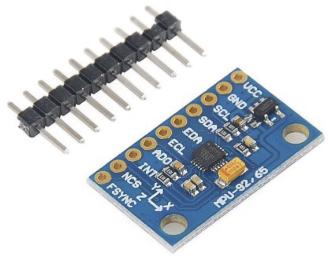

Figure 6. Schematic of accelerometer sensor(InvenSense 2014).

3 COMMUNICATION WAYS

While many sensors use digital and analog ports for uploading the measured data to the microcontroller, some sensors use the inter-integrated circuit (i2c) protocol. This is a protocol that allows multiple "slave" digital integrated circuits (sensors) to communicate with one or more "master" chips (arduino). Like the serial peripheral interface (spi) which is only intended for short-distance communications within a single device. The ultrasonic sensor and dht22 have been connected to the arduino's digital ports. The laser and the accelerometer had to be connected to i2c port (scl, sda) on the board.

All the different types of ranging circuits have been connected and glued together, so data from all 3 of them would be measured almost simultaneously on the static experiment. A different circuit had to be made for the accelerometer, in order to perform the dynamic experiment. Finally, 2 different codes were written on the Arduino platform and uploaded to the board via a usb cable. In addition, a Raspberry Pi which is a small size Linux-based computer that can be connected to Arduino microcontrollers, was used as the wireless file server in this study (Komarizadehasl, Lozano Galant, et al. 2022b). This way, the operator can access the Arduino codes for modifying or upgrading purposes (Komarizadehasl, Lozano Galant, et al. 2022a). To save and acquire provided data of the accelerometers, a python code was written to save the acquisition data on the Raspberry Pi memory card. For getting the main characteristics of these sensors, a few dynamic and static tests have been carried on.

4 STATIC EXPERIMENT

The device was tested against for the purpose of same measurement against different materials. In the static experiment, tests with and without extreme ambient light has been done for getting the distance from the big book. For the one with the light bulb, the temperature sensor has been moved a bit far from the source of the light and heat. The reason was that the excruciating heat coming from the light bulb would not harm the sensor. standard deviations driven from the performed tests has been illustrated. On Table 1 ranging result of same experiment under different circumstances has been shown.

Table 1. Results of ranging experiments.

Sensors	Thick book	White paper	Black paper	Tissue	Transparent plastic cover	Extreme ambient light
Ultra	0.61	1.87	1	352	0.7	3.23
Laser	2.5	2.67	7.18	4.66	5.46	3607

It should be mentioned that the ultrasonic sensor which was the chipset sensor and the easiest one to install, had shown better performances compare to the laser ones. On down side, this sensor needs 5v interaction digital ports and needs at least 4 volts for its full functionality. The only problem with this sensor could be its data providing speed. Although the laser has a faster rate (50Hz data production), this sensor has a frequency of only 20Hz. In other words, this sensor can provide up to 20 data each second. The biggest problem with the ultrasonic sensors would be their dependence on the ambient temperature and humidity. Since the speed of sound changes from an environment to another. This sensor needs the accurate speed of sound for its calculations. The proposition of this paper would be using the ultrasonic sensor with a laser sensor if there was the probability of a changing temperature or of an extreme ambient light. Using the first laser sensor or the second one is due to what range and circumstances the experiment may experience.

5 DYNAMIC EXPERIMENT

For testing the accelerometer sensor and its reliability, an experiment has been implemented. With a dynamic jack, a sinus signal has been programed and the vibrations had been saved by the accelerometer. This jack can shake its bottom plate as was programmed. The instructions to the hydraulic jack was to make a wave with a fixed frequency 5 hertz (5 complete waves in one second). The movement of the jack was to go up to 0.1 millimeter up and -0.1 millimeter down from its null axis to make a sinus wave. With a very simple two time differential, the acceleration equation could be calculated.

$$y = d * \sin(\omega * t + \varphi) \tag{1}$$

$$\omega = 2 * \pi * f \tag{2}$$

In the above equation y is the displacement in time t, d is the maximum allowed movement of the jack in each cycle, ω is the angular frequency and f is the set frequency which equal to 5Hz and φ is the phase constant. On the equ.3, acceleration has been calculated from the equ.1 and equ.2. this was done by getting the second order derivative of the equ.1. By putting all the data in the equ.3 the maximum acceleration was calculated as 10.4352 g*10-3 m/s2.

$$a = \frac{d^2 * y}{dt^2} = \ddot{y} = -d * \omega^2 * \sin(\omega * t + \varphi) \tag{3}$$

The very first faced problem in this experiment was that the sensor could not record data or if recorded, the data were messy. It was deducted that the sensor had to be glued to the bottom plate of the jack for getting accurate information. The second problem was that the written python code could save only 120 data per second while the sensor was reporting more than 300 data per second. Although by using a serial port commercial software on the computer it could have been possible to save data with the same speed of their production. Since here getting the accurate time of capture was vital, it was obligatory to use python to attach the provided data with their corresponding time. To tackle this problem, the speed of data capture had to be dialed down, so the python could get and save them. To be on the safe side the speed of capture had been set on 84Hz.

The other unexpected issue that this project faced was that, though this sensor had been calibrated in the company, it had a constant number added to all provided data which from now here it would be named as the white noise. As on the Figure 7a it has been illustrated, the averaged data is around -50milig while they had to fluctuate around zero. This -50milig was considered as the white noise of this sensor. In order to measure this correctly, the average of 10000 set of data in a vibration free test has been calculated. For this sensor the white noise had been calculated as -49.8535 milig. By removing this amount from the provided accelerations, the values had been pulled up where they needed to be. The data were clearer and more understandable when this white noise had been removed. This improvement can be seen on Figure 7b.

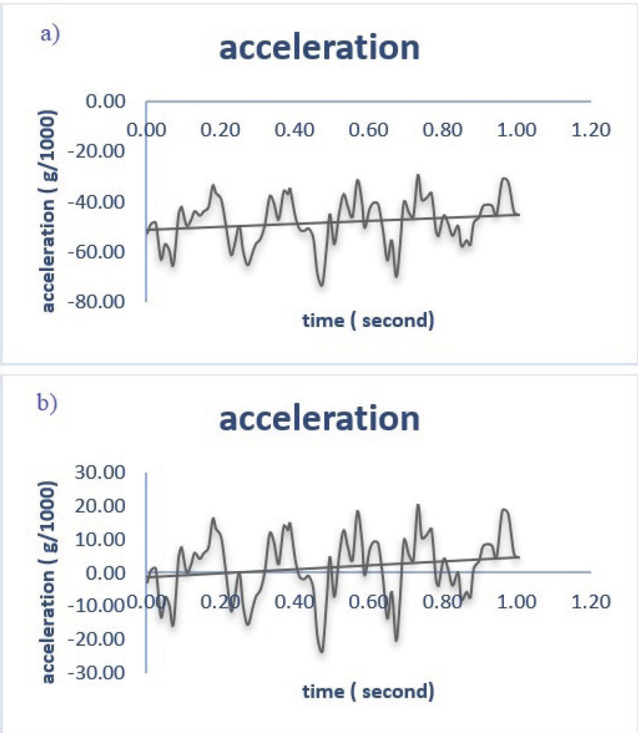

Figure 7. 7a shows Acceleration, Time diagram with white noise & 7b shows Acceleration, Time diagram without the white noise.

6 CONCLUSIONS

Notwithstanding that the laser sensors did not have as good results as the ultrasonic one, they can be useful as well. They are smaller, they are lighter and faster and have noise-free technology (no noise can enter from the wires). Moreover, they work inde-pendent of the temperature of their testing situation. Best results would only appear if an ultrasonic sensor (attached to its temperature and humidity sensor) be used alongside of a Laser sensor. They can cover the downsides of each other and provide accurate, useful set of data.

As on the Figure 7b it is visible the sinus wave conducted from the accelerometer is quite close with the expected behavior. As it is observable the sinus wave is fluctuating about 10.5 milig from its average. As it was calculated on the last section the graph should have had a 10.453 milig fluctuation. It is quite notable to see that they have worked out almost the same.

On the Figure 7b the filtered data from the 5Hz experiment has been shown. As it can be seen, the result is not so accurate, for the fluctuation has other unexpected data or noises as well. In the future works, filters must be applied to delete the unwanted data and ambient noises which may have entered in to this experiment unwantedly.

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