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A novel low-cost inclinometer sensor based on fusion technology for structural health monitoring applications

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ABSTRACT: The fundamental purpose of structural health monitoring (SHM) is to examine the accuracy of the structural health state and predict its future strength. Lately, researchers have been paying close attention to the structural damage detection process employing inclinometers. However, this technique can only be used with unique structures with a sizable Structural Health Monitoring (SHM) budget due to the high cost of inclinometers. Therefore, the use of low-cost sensors by implementing various techniques to improve their accuracy compared to high-cost precision sensors has attracted much attention for structural assessment. This paper introduces a novel, low-cost inclinometer that measures inclination by fusion technology combining gyroscopes and accelerometers. The microcontroller technology used in this gadget is an open-source Internet of Things (IoT) based platform, allowing for wireless data streaming and free commercial software for data collecting. Not only are the coding and placement issues of these sensors thoroughly explained, but detailed answers to the problems mentioned above are also provided, as well as an efficient way to assemble and prepare the sensors.

1 INTRODUCTION

Structural Health Monitoring (SHM) has attracted the attention of engineers over the past decades as a control system to measure the structural response of structural elements to prevent future potential failures in civil infrastructures. A number of factors and situations such as construction defects, fatigue and environmental factors might decrease the structure's serviceability and safety over time (Kaloop et al., 2022), (Mahyad Komary et al., 2022), (Seyedmilad Komarizadehasl et al., 2022). Therefore, monitoring and assessing structures' health state throughout their life cycle are essential to minimize the future reparation costs and to confirm the Structural safety and serviceability (Proske, 2020), (Farré-Checa et al., 2022). SHM applications provide vital information about the actual structural response of infrastructures, the condition of the structures and their performance (Mahyad Komary et al., 2023).

For measuring static and dynamic responses, sensors are widely used in SHM systems (S. Komarizadehasl et al., 2022). Accelerometers are commonly used for monitoring the dynamic response of the structures, while the most common sensors for static measurements include strain gauges, inclinometers and thermometers (Lei et al., 2021), (M. Komary et al., 2022).

Even though accelerometers can detect global structural damages to a structure, they traditionally fail to detect the damage location and its severity (Hester et al., 2019). Displacement

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sensors such as Laser Displacement Sensors (LDS) can be used in load tests to help to locate the damage and its extension as long as a particular reference point exists (Raghuwanshi & Parey, 2018), (Yao et al., 2022). Unfortunately, a number of limitations on-site can make the proper definition of the required reference points difficult (Park et al., 2013). Alternative strain-type sensors can be used to evaluate the extent of the damage and its location. In fact, this type of sensor has shown remarkable accuracy and applicability in the literature (Li et al., 2020), (Iriarte et al., 2021), (Copertaro, 2022). However, a large number of this type of sensor might be needed to monitor the structure's structural properties entirely.

In order to overcome the drawback of the aforementioned sensors, inclinometers can be used. Angular sensors (inclinometers, tilt sensors) are manufactured to estimate the angular rotation of a target object respected to an artificial horizon (Hester et al., 2019), (Seyedmilad Komarizadehasl et al., 2022). Most inclinometers follow the principle of measuring responses induced by pendulum behaviour due to gravity (Huseynov et al., 2020). Furthermore, this slope can be used to calculate the drift of vertical members and vertical deflection of the horizontal elements (Ha et al., 2013).

Table 1 illustrates the characteristics of some of the commercially available inclinometers and is sorted by the price of the sensors. It should be noted that prices are based on the recent producer declaration and are VAT excluded.

Table 1. Characteristics of some of the commercially available inclinometers.

Model	Sampling Rate (Hz)	Resolution (Degrees)	Measurement Range (Degrees)	Price (€)
ZEROTR ONIC	10	100×10-5 °	± 0.5°	3950
ACA2200	20	10×10-5 °	± 0.5°	710
HI-INC	100	100×10-5 °	± 15.0°	650
ZCT-CX09	8	100×10-5 °	± 15.0°	350
DNS	100	300×10-5 °	± 85.0°	348

Analysis of Table 1 shows a wide range of prices (varying between 350€ up to 3950 €) and measurement ranges (varying between 0.5 and 85.0 degrees). It can be seen that inclinometers with a lower range have a higher resolution and price. Furthermore, inclinometers with higher resolution typically have higher costs and lower sampling frequencies.

On the contrary to the benefits of using inclinometers (Hester et al., 2019), this monitoring system presents limited precedents in the literature of SHM of bridges (Erdenebat et al., 2018), (Alten et al., 2017). Among the reasons given by Huseynov (Huseynov et al., 2020) to explain the lack of the use of the inclinometers is to highlight the lack of sensor technology, low-frequency sampling, and the cost of the current inclinometers.

To solve the aforementioned drawback of inclinometers, low-cost sensors can be used. In fact, Micro-Electro-Mechanical Systems (MEMS) accelerometers have revolutionized the measuring applications with reduced size and price (Seyedmilad Komarizadehasl, Lozano Galant, et al., 2022a). It should be noted that other low-cost MEMS accelerometers were already published for SHM applications in the literature.

MEMS sensors are typically coupled with gyroscopes. MEMS Gyroscopes measure the angular rate by Coriolis acceleration, enabling the rotational speed measurement. The main drawback of the gyroscopes is bias instability or Flicker noise (Hiller et al., 2019).

Almost all current MEMS inclinometers use sensor fusion capability to improve the individual drawbacks of the accelerometer and the gyroscope. In addition, the negative impacts of a sudden movement of the accelerometer estimations are controlled with the gyroscope measurements (Ghasemi-Moghadam & Homaeinezhad, 2018).

The literature review shows no accurate, low-cost inclinometers based on the Arduino or NodeMCU technology that could be used in SHM of bridges due to the special peculiarities of this type of monitoring (Huseynov et al., 2020). To fill these gaps, this paper presents, for the first time in the literature, a Low-cost Adaptable Reliable Angle-meter (LARA) system for SHM of bridges. LARA is a low-cost wireless inclinometer based on an IoT-based microcontroller (NodeMCU) technology with an accuracy of 0.003 degrees based on the performed experiments of this paper.

LARA is based on MEMS technology and uses the complementary filter to couple the outputs of its accelerometer and gyroscope calculated angles.

In addition, to build an inclinometer with higher accuracy, better resolution and lower noise density, this paper develops a custom-designed Printed Circuit Board (PCB) containing five low-cost aligned MEMS MPU9250 chipsets, each of one incorporating a gyroscope, an accelerometer and a magnetometer (Seyedmilad Komarizadehasl, Lozano Galant, et al., 2022b).

2 THE PROPOSED INCLINOMETER

2.1 *Low-cost Adaptable Reliable Angle-meter (LARA) system*

2.1.1 *Hardware architecture of LARA*

This paper proposes multiple combinations of gyroscopes and accelerometers for producing a more accurate inclinometer. To this end, five chipsets of MPU9250 are engineered together on a single PCB and synchronized using a multiplexor (TCA9548A). To avoid the problems of a manual fabrication (such as nonalignment of the circuits, time-consuming process of aligning, soldering and sensor quality control and size), the PCB of LARA was designed and produced to satisfy the delicacy of current project measurements. In addition, the required components of LARA are soldered to the PCB using machine assembly. The cost of a LARA made by connecting five MPU9250 and TCA9548A and a bulk company-produced PCB with assembled components is around 37 and 51 €, respectively.

As shown in Figure 1.a, LARA has four output ports. These wires should be connected to a microcontroller to power up the sensors, acquire the sampled data, and convert the gyroscope and the accelerometer to tilt and pitch inclination. The used microcontroller of this paper is NodeMCU and shown in Figure 1.b. This low-cost open-source Internet of Things (IoT) platform runs on the ESP8266 chipset. ESP8266 is a low-cost WiFi microchip with the Internet protocol suite (also known as TCP/IP) capability (Chiesa et al. 2020).

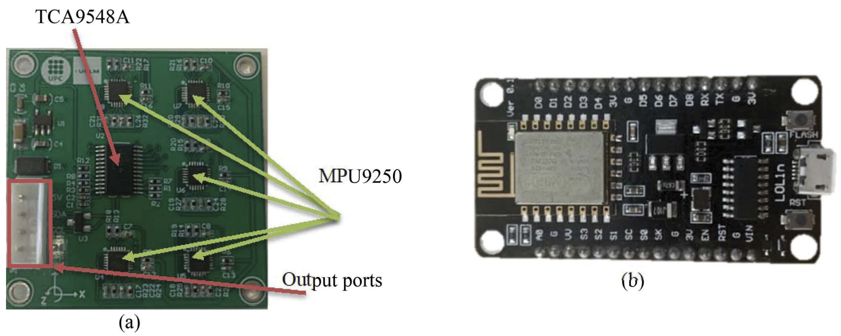

Figure 1. Illustration of LARA: (a) The produced product, and (b) NODE MCU microcontroller.

2.1.2 *Software architecture of LARA*

In this section, the used software for this project is presented in the following:

Arduino platform: NodeMCU is first programmed using the Arduino platform. This program first estimates the angle in real-time from each of the individual MPU9250 chipsets. Then, the formulas for calculating the rotation using a triaxial accelerometer for X and Y axes are presented in Eq.1 and Eq.2, respectively.

$$angleaccX = tan^{-1}\left(\frac{accY}{\sqrt{accZ^2 + accX^2}}\right) \times \left(\frac{360}{2\pi}\right) \tag{1}$$

$$angleaccY = \tan^{-1}\left(\frac{accX}{\sqrt{accZ^2 + accY^2}}\right) \times \left(\frac{360}{2\pi}\right) \tag{2}$$

In Eq.1 and Eq.2, where, *angleaccX* and *angleaccY* are the calculated angles from the acquired data of a MPU9250 accelerometer around the X-axis and Y-axis, respectively. The *accX*, *accY and accZ* represent the obtained acceleration data of X, Y and Z axes. Eq.3 and Eq.4 present the used complementary equation for the fusion of the gyroscope and the accelerometer results for measuring the rotation around X and Y axes, respectively.

$$angleX = (0.96 \times (angleX_0 + gyroX \times time)) + 0.04 \times angleaccX \tag{3}$$

$$angleY = (0.96 \times (angleY_0 + gyroY \times time)) + 0.04 \times angleaccY \tag{4}$$

In Eq.3 and Eq.4, where, *angleX* and *angleY* are the final calculated rotations around X and Y-axes, respectively. The $angleX_0$ and $angleY_0$ are the estimated angle of the system from the previous measurement. The *GyroX* and *GyroY* represent the measured angular speed of the gyroscope for X and Y axes, respectively. The *time* presents the interval time between two measurements. Further analysis of these equations shows that the angle calculated from the accelerometer is multiplied by a smaller coefficient than that of the gyroscope (Yi et al., 2018). This low coefficient factor of *angleacc* is for mitigating the impact of environmental vibrations (also known as cross-talk of vibration) and can vary between 0.02 and 0.05 (Shen et al., 2012).

Data acquisition: Unlike the Arduino platform, free commercial software like SerialPlot can represent the sampled data in real-time in a graphical interface and save the data with the date and timestamp of data acquisition.

3 STATISTICAL REPRESENTATION OF COMBINING DYNAMIC-SENSOR THEORY

3.1 *Noise reduction of Inclinometers*

It was noticed that the average value of outputs of several aligned synchronized inclinometers has lower noise density than the those of a single one. The standard deviation of up to five combined inclinometers is presented in Figure 2.

The analysis of Figure 2 shows that the higher the number of sensors considered the lower the noise density of their averaged measurements that the more combined inclinometers have a lower noise density. The reason behind the beneficial behaviour of combined inclinometers is within the inherent dynamic noises of the produced accelerometers and gyroscopes chipsets.

These results led to investigating the beneficial impact of dynamic sensor combinations. Analysing the individual outputs, the five used MPU9250 sensors showed that every single sensor has unique dynamic noises.

By improving the noise density, the inclinations that in the first place were smaller than the noise density of the sensor can now be detected due to the improved noise level.

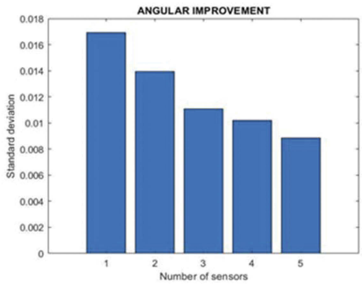

Figure 2. Representation of the noise ratio of a single and up to five combined inclinometers using standard deviation.

4 LABORATORY EXPERIMENTS

4.1 *LARA resolution and accuracy verification using a beam model*

In order to present the resolution and accuracy of LARA more clearly, a load test is performed on a small-scale beam with a length of 1.24m. This section compares the slope estimation of two sensors (LARA and H-INC) located on the support of a simply supported aluminium beam model under a point load of 467 gr (4.58 kN) with hand calculation of slope at the beam edges.

This test is carried out using a U-shaped aluminium profile with section dimensions of 25×25×3×3 mm. The effective length of the beam model, which is the distance between the null axis of its support, is fixed as 1080 mm.

The test aim was to read the maximum slope of the beam model deck under a known applied load on the mid-span. The maximum slope at the supports can be calculated by Equation 5. Therefore, LARA and HI-INC were attached to achieve this objective on top of the beam model support. First, LARA and HI-INC worked for a while without any loads and their estimations were acquired. Next, the point load was set on the mid-span of the beam model (Figure 3) and then another data acquisition process was carried out to measure the slope of the beam by LARA and HI-INC. It is essential to mention that this test was repeated three times.

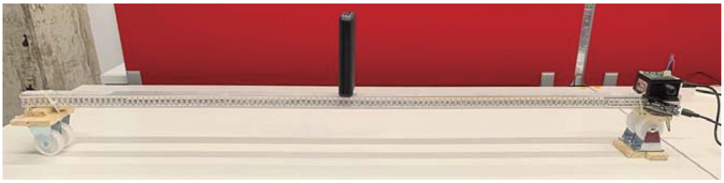

Figure 3. Load test of a beam model.

The used formula for calculating the slope of a simply supported beam with a load located on its midspan by hand is presented in Eq.5 (Hibbeler, 2017).

$$\Delta\theta_1 = \frac{P \times L^2}{16 \times E \times I} \tag{5}$$

In Eq.5, where, $\Delta\theta_1$ (Radians) is the maximum slope at the supports, P is the value of the applied load at the mid-span, L is the effective beam length, E (69637.05 MPa) is the beam elasticity module, and I (12853.08 mm^4) is the beam moment of inertia.

Table 2. Comparing the inclination estimation of LARA and HI-INC.

Number of the experiments	Hand calculation slope (degrees)	LARA Difference (degrees)	LARA (degrees)	HI-INC difference (degrees)	HI-INC (degrees)
1	0.021372	0.001613	0.022985	0.002447	0.018925
2	0.021372	0.002316	0.023688	0.000853	0.020519
3	0.021372	0.001362	0.022734	0.005196	0.016176

The analysis of Table 2 shows that the accuracy of LARA based on these experiments is less than 0.002 degrees. Further study of Table 2 illustrates that the accuracy of HI-INC is around 0.005 degrees. In fact, this is very close to accuracy value detailed in its datasheet (±0.003° for ±15° version).

Another experimental test was carried out on this beam model using a heavier weight (21.942 N). In this experiment, instead of putting the weight only on the midspan, the weight was set on various beam locations.

Figure 4 presents the slope measurement comparison of HI-INC and LARA with the hand calculation values. It is vital to mention that this experiment is carried out on the same beam model presented in Figure 3. As showed in this figure, the inclinometer is mounted on a pinned support.

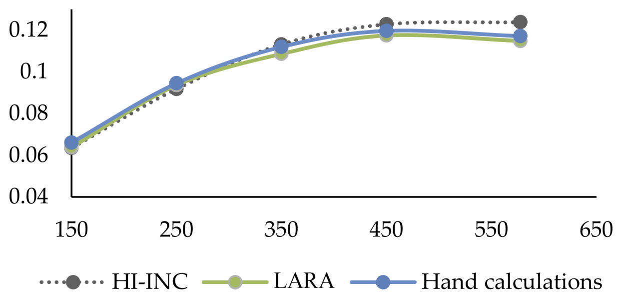

Figure 4. Support slope of a simply supported beam under a point load located on various spots.

Analysis of Figure 4 shows that LARA has a maximum measured difference of 0.003 degrees from the hand calculation slope. In addition, it can be seen that LARA has a closer trend to the hand calculation values compared to those of HI-INC.

It can be seen from Table 1 that HI-INC, ZCT-CX09 and DNS have a resolution of 0.003 degrees. Therefore, LARA can be compared with them. Figure 5 presents the price comparison of these inclinometers.

Analysis of Figure 5 shows a significant difference between the price of LARA and inclinometers with the same resolution. LARA is 12, 6 and 6 times cheaper than HI-INC, ZTC-CX09 and DNS inclinometers, respectively. Also, it does not need extra paid commercial software for data acquisition, and it is based on open-source software and hardware.

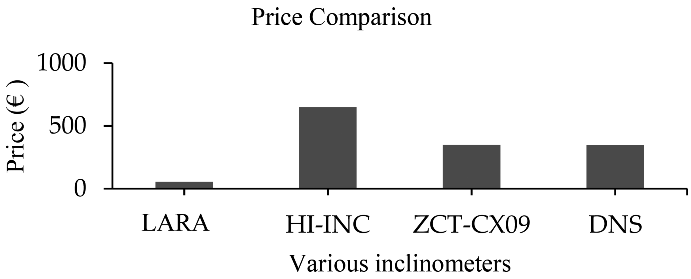

Figure 5. Price comparison of LARA with traditional commercial inclinometers with a resolution of 0.003 degrees.

5 CONCLUSION

Lately, the implantation of inclinometers for SHM of bridges is receiving a lot of attention from engineers and researchers. In fact, unlike accelerometers, inclinometers can enable easily the evaluation of both the location and severity of the structural damage. This characteristic makes them suitable for long-term Structural Health Monitoring (SHM) of bridges. However, the current inclinometers' high price has limited their use. There is gap in the literature with the development of a low-cost inclinometer for long term SHM of bridges with a low budget for their health assessments.

To fill these gaps, in this paper, a Low-cost Adaptable Reliable Angle-meter (LARA) system is presented. LARA is a low-cost wireless IoT-based inclinometer with a sampling frequency of 250 Hz. The main novelty of LARA is combining the results of five aligned inclinometers for reducing the inherent noise density of individual accelerometers and gyroscopes of LARA.

In order to validate the assumption of noise reduction and signal improvement of inclination measurements using the averaged results of several aligned inclinometers, four laboratory experiments were carried out. The results of tests show that averaging the values of a number of aligned accelerometers reduces the noise density of the frequency domain representation of a vibration acquisition experiment.

In addition, in order to compare the accuracy of the used commercial inclinometer and LARA a load test is performed on a beam. In this test, the reported values of the commercial inclinometer are compared with LARA's. It is shown that LARA estimated the theoretical slope with less than 0.003 degrees of difference from the hand calculated values. However, HI-INC showed an accuracy higher than its datasheet data with a magnitude of ±0.005°.

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