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Prototype of simple mini-wave gauge using Microcontroller ESP32 on the laboratory scale

Rikha Widiaratih[1*], Agus Anugroho Dwi Suryoputra[1], Gentur Handoyo[1], Alfi Satriadi[1], and Ari Bawono Putranto[2]

[1]Department of Oceanography, Faculty of Fisheries and Marine Science Universitas Diponegoro, Jl. Prof. H. Soedarto, S.H, Tembalang, Semarang, Central Java 50275 Indonesia
[2]Department of Industrial Technology, Vocational School Universitas Diponegoro, Jl. Prof. H. Soedarto, S.H, Tembalang, Semarang, Central Java 50275 Indonesia
*Corresponding author: rikha.widiaratih@gmail.com

Abstract. The limited availability of real-time wave data is needed for shipping safety and for planning coastal areas. This wave data monitoring system including the wave height and direction gained to be used as a consideration in making decisions related to shipping safety and coastal management. This study aims to design and create a prototype of a simple mini-wave gauge and test the performance of a mini-wave gauge on the laboratory scale. The sensors used in this mini-wave gauge were ADXL335 as a vibration sensor to detect wave movement and the GY-271 sensor module with the HMC5883L chip which was a direction sensor. In the experiment, the wave data generated by the sensors were then received by the microcontroller ESP32 as a data processing center. The wave data was then received by the computer using a Wi-Fi network as well as processed and displayed on an application that had been developed using Embarcadero Delphi. Experiments with this mini-wave gauge resulted in an average range of wave height ± 6cm with a wave trough of -4.5 cm and a wave crest of 2.2 cm. This mini-wave gauge was then validated with the ultrasonic sensor at laboratory scale and the root mean square error obtained was 1.34 cm. Generally, this device functions well and has high accuracy for recording wave data.

Keywords: microcontroller ESP32, mini wave gauge, real time, wave direction, wave height

1. Introduction

Waves have an important role in life, such as maintaining the stability of temperature world's climate [1], preserving levels of Dissolved Oxygen (DO) [2], maintaining a mutualistic symbiotic relationship in marine organisms [3], sports facilities [4], forming beaches by abrasion and sedimentation processes [5], fisheries [6], shipping [7], early warning of natural disasters [8], renewable energy [9] and necessary for coastal buildings planning [10]. Moreover, in the field of Oceanography, it uses to verify the results of wave modelling [11]. Nowadays, direct measurements of waves have limitations, especially the high cost of procurement equipment such as using the Acoustic Doppler Current Profiler (ADCP) for field measurements, while measuring instruments that are available at affordable prices are still challenges in technology [12]. Even though, waves data able to be obtained through satellite approaches, such as those derived from the European Centre for Medium-Range Weather Forecasts (ECMWF) and Marine Copernicus, however, still limitations regarding the spatial resolution of waves data ±9 km, which conditions unable to be applied to small-scale areas and shallow areas [13].

The importance of wave's real data leads this research for creating a simple prototype of a mini-wave gauge to obtain wave data. Moreover, it is capable to be used as monitoring data for the practical benefit of coastal areas. There were previous studies related to constructing a prototype of a wave measuring device, namely in the form of a buoy was compared to the wave rider and showed a bias data of 4.0 cm [14], other using the wave buoy of the Global Navigation Satellite System (GNSS) which had a measurement bias of 3.4 cm [15]. Furthermore, the wave-measuring device prototype using the Arduino Uno Microcontroller showed good results with an accuracy rate of > 95% [16][17].

The high demand for waves in real-time with affordable cost inspires this research to create a simple mini-wave gauge prototype with functions well and has high accuracy. The expectation of the simple prototype of a mini-wave gauge in the future is that it can be used as a monitoring tool for coastal planning purposes such as coastal building, regional zoning, and natural disaster mitigation [18]. In earlier studies, mostly the sensor used to measure wave height used an ultrasonic or Arduino Uno microcontroller sensor. However, in this study used the ADXL335 sensor would be implemented by utilizing the vibration effect which would be converted to wave height, and the GY-271 sensor equipped with the HMC5883L chip to determine the direction of the incoming waves. Moreover, this sensor was constructed using the microcontroller ESP32 as the brainpower for the processing unit.

Nowadays, many applications are developed using Internet of Things (IoT) principles. The concept of IoT is to create it easier for users to carry out monitoring without having to take direct field data, which is supported by an internet connection. The concept of IoT is the devices embedded by the sensor and then connected to the internet, then users can get the data in real-time [19]. This research is focusing on the function of the mini-wave gauge device for measuring wave height. Moreover, the calculation of the accuracy of wave height measurements from mini-wave gauge was achieved by comparing with wave height data measurement derived from the ultrasonic sensor in a wave flume on a laboratory scale using the IoT concept.

2. Materials and Methods

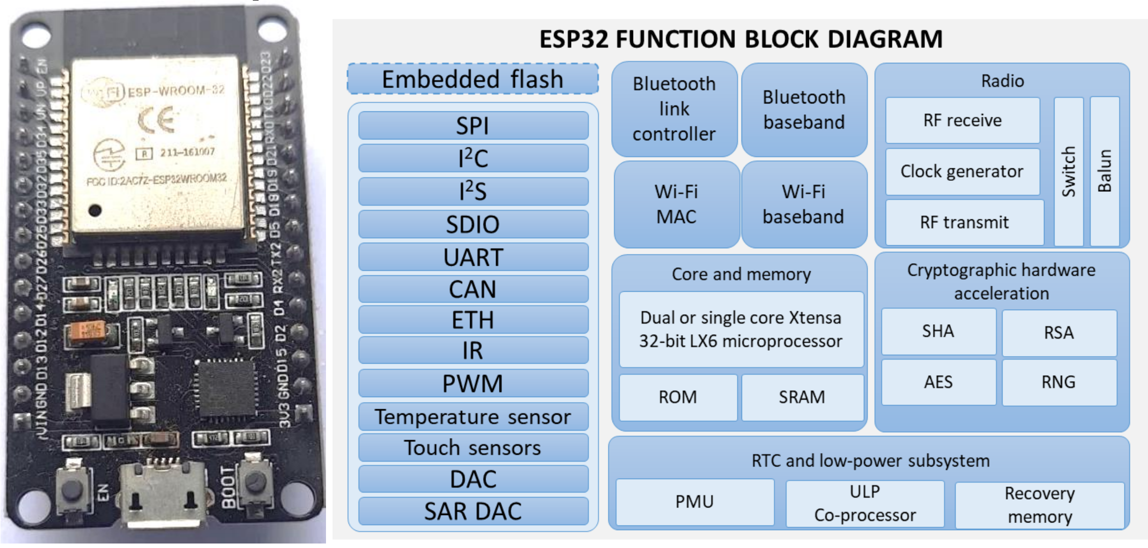
The materials used in constructing this mini-wave gauge prototype consist of ready-made sensors, which were then assembled using a programming language so that the sensor could record data according to user needs. The method used in this research was the experimental method, which was then built as the prototype of a mini-wave gauge to measure the height and direction of the waves. Furthermore, the examination of the accuracy of this mini-wave gauge then compares with the ultrasonic sensor data in the wave flume in the Hydrodynamics Laboratory, Faculty of Fisheries and Marine Sciences, Diponegoro University.

2.1 Materials

The prototype of the mini-wave gauge generally was arranged into five main components as shown in Figure 1-5. The main components of the mini-wave gauge were composed of a Microcontroller ESP32, ADXL335 accelerometer sensor, GY-271 direction sensor, Li-ion battery 18650 Voltage 3.7volt, and LM2596 Step down sensor module. The microcontroller ESP32 is a platform that functions as the brain that regulates data processing and the resulting output [20][21]. The ADXL335 accelerometer (vibration) is a sensor that functions to measure wave height obtained from a vibration approach [22]. GY-271 direction sensor (compass) has the role is to obtain wave direction data [23]. Li-ion battery 18650 Voltage of 3.7 volts which functions as a power supply, supports all sensors to get the energy supply to function normally [24]. And last, there is the LM2596 Step down sensor module which functions to decrease the input voltage [25].

2.1.1 Microcontroller ESP32

The microcontroller ESP32 is made by expressive systems, a low-cost, low-power minimum system microcontroller Series on Chip (SoC) series with Wi-Fi & Bluetooth capabilities [26]. The ESP32 family includes the ESP32-D0WDQ6 (and ESP32-D0WD), ESP32-D2WD, ESP32-S0WD, and ESP32-PICO-D4 System-in-Package (SiP) chips. At its core, there is a dual-core or single-core Tensilica Xtensa LX6 microprocessor with a clock rate of up to 240 MHz. The ESP32 is integrated with built-in antenna switches, RF balun, power amplifier, low noise receives amplifier, filters, and power management modules (Figure 1(a)). The microcontroller ESP32 is designed for mobile devices, electronic devices, and IoT applications. In addition, microcontroller ESP32 also works with very low power consumption through power-saving features including fine resolution clock gating, multiple power modes, and dynamic power scaling. The components on this microcontroller are almost like an ordinary computer device that has a Central Processing Unit (CPU), also equipped with RAM, ROM, and input and output devices (IO ports) that can be programmed as needed. The use of this microcontroller is generally applied to devices that require automatic control [27].



(a) (b)

Figure 1. Microcontroller ESP32 (a), Aarchitecture of mikrokontroler ESP32 (b)

The microcontroller ESP32 module is the successor of the ESP8266 module which is quite popular for IoT applications. The ESP32 has a CPU core as well as faster Wi-Fi, more GPIO, and supports Bluetooth Low Energy. Figure 1(b) is described the architecture of the ESP32 microcontroller.

2.1.2 Sensor ADXL335

An accelerometer sensor is a sensor that is used to measure speed or as an accelerometer sensor or vibration sensor tool [28]. This acceleration sensor module adequately identifies or measures both static and dynamic. This measurement is based on moving objects and gravity. Static speed measurement occurs by focusing on the earth's gravity, while dynamic measurements focus on moving objects (vibrations) [29]. The ADXL335 sensor module is an accelerometer sensor module that has 3 analog outputs for vibrations in the x, y, and z directions (Figure 2).

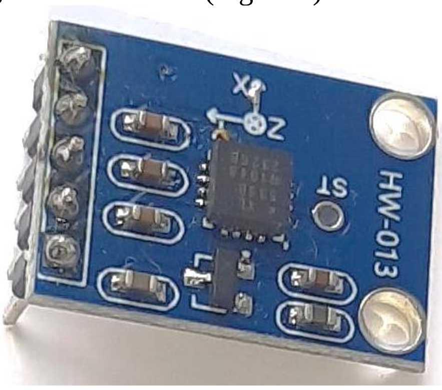


Figure 2. Sensor ADXL335 accelerometer (vibration)

2.1.3 Sensor GY-271 Direction (Compass)

The direction (compass) is a sensor used to determine direction based on the poles of the Earth's magnetic field. A sensor is a tool that functions to detect symptoms originating from energy changes [30]. Several chips provide digital compass capabilities, one of the most common being the HMC5883L, a 3-axis digital compass chip (Figure 3). These chips were packaged with several companies, but almost all of them produced a similar interface. This type of digital compass uses a magnetic sensor to measure the Earth's magnetic field. The output from the sensor is then accessible from outside through a set of registers that allow the user to set things like the sample rate and continuous or single sample. The X, Y, and Z directions are outputs that also use registers. The compass sensor functions as a wave direction pointer. This module is very suitable to be connected to the Arduino microcontroller, ESP8266, ESP32, or a similar minimum system that is compatible with the I^2C communication protocol [31]. Examples of applications that have used this sensor a lot are smart cars, quadcopters, robotics devices, and others.

Figure 3. Sensor GY-271 direction (Compass)

2.1.4 Circuit of Data Supply Battery 3.3 Volt

This device used a lithium-ion battery (Li-ion 18650) for power supply with each rechargeable battery voltage of 3.7 volts (Figure 4(a)). There were 2 batteries used in this device, and they were connected in series to produce a total voltage of 7.4 volts. Then after getting a total battery voltage of 7.4 volts, the voltage was regulated or reduced to 3.3 volts using the LM2596 step-down module (Figure 4(b)). The use of a step-down module was to adjust the working voltage of the microcontroller ESP32, and all the sensors used. Utilizing the LM2596 step-down module and 7.4-volt battery supply would make the 3.3-volt power supply to the microcontroller and sensor circuit more durable because it anticipated a drop in voltage from the battery when it was being used. The LM2596 step-down module should maintain a stable output voltage of 3.3 volts during use if the total regulated battery voltage was still above 3.3 volts. One type of rechargeable battery is the lithium-ion battery. Its constituent components consist of a cathode, anode, electrolyte, and separator. Lithium ion has the advantages of faster charging, long-lasting usage, and being lightweight but has a large power capacity [32]. The advantage of using Lithium batteries is that they have a greater power and energy density than other types of batteries, but on the other hand, they have disadvantages, namely being sensitive to overcharging [33]. While the LM2596 DC-DC step-down module is an adjustable DC to DC voltage step-down regulator module. The input voltage range was 4v-40v with an output of 1.23v-35v. The maximum current limit was up to 2A with protection in the form of a short circuit current limiter [34].

(a) (b)

Figure 4. Li-ion battery 18650 Voltage 3,7 volt (a), Step down module LM2596 (b)

2.2 Flowchart

The flowchart is a description of the flow of how the system works sequentially. In general, the work process or flowchart of the prototype mini-wave gauge is illustrated in Figure 5. The microcontroller ESP32 acted as the brain for processing data connected to input from the ADXL335 accelerometer sensor for vibration to get wave height and the GY-271 direction sensor (compass) for the direction of incoming waves. Furthermore, wave height and wave direction data were sent to the display or output using Wi-Fi for acquisition data. To support this electronic work, the microcontroller ESP32 was supported by 2 Li-ion batteries 18650 Voltage 3.7 volts as a source of energy. The microcontrollers ESP32 are widely used in many studies, due to being affordable, simple, and having good resistance [35]. In addition, the microcontroller ESP32 has the flexibility of its users in carrying out various experiments, such as remotely a device, connected to Wi-Fi, Bluetooth, and the Internet of Things [36].

The block diagram device illustrated the working system of the tool to make it easier to understand. The block diagram device of the mini-wave gauge is depicted in Figure 5. Overall, this system consisted of several parts which could be shown with a system block diagram [37]. The wave data acquisition system used a computer application with the Microsoft Windows operating system to retrieve data directly. This data acquisition application was created using the Delphi programming by utilizing the TCP/IP socket component features to receive data from the microcontroller ESP32 via a Wi-Fi network. Utilizing a Wi-Fi network between a computer or laptop and the microcontroller ESP32 was enough to conduct wave measurement research on a laboratory scale wirelessly.

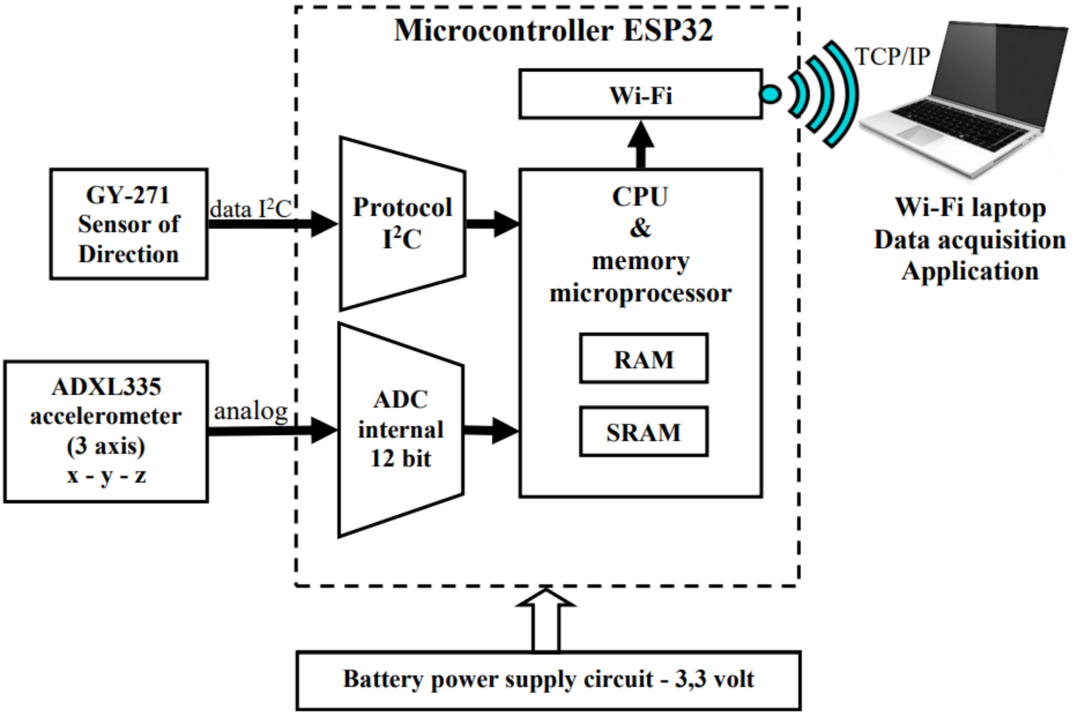


Figure 5. Block diagram device of mini-wave gauge

A schematic of the circuit of the mini-wave gauge is depicted in Figure 6. A printed circuit board (PCB) is a board that conductively connects electronic components to tracks, pads, and vias of copper sheet laminated on a non-conductive substrate. PCBs can be in the form of 1 layer, 2 layers, or many layers (multilayer). PCBs can be found in almost all electronic equipment such as mobile phones, televisions, cars, motorbikes, and others. Many things must be considered by a designer to be able to design a printed circuit board that can function according to the specified specifications. Furthermore, the real picture of the inside of the simple mini-wave gauge is presented in Figure 7.

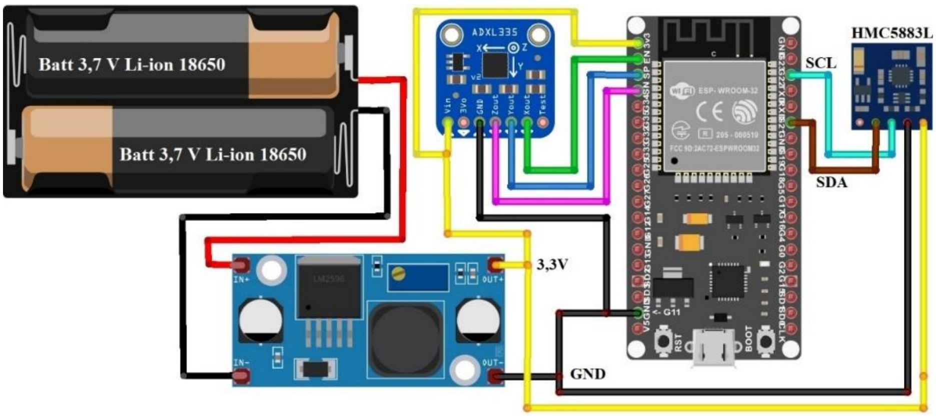


Figure 6. Scheme of Circuit

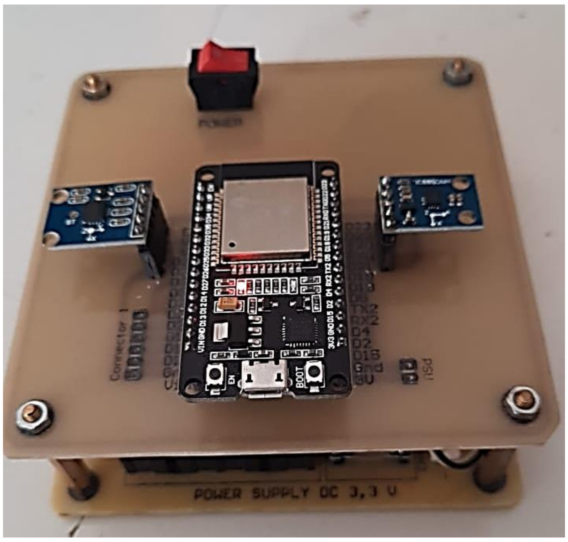


Figure 7. Inside the mini-wave gauge

2.3 Programming Language

Microcontroller is a chip that functions as a controller or control of electronic circuits and could generally store programs in it. A microcontroller is a minicomputer device (micro) that is packaged in a single IC (Integrated Circuit) chip and has certain programs in it. There were 2 types of programming languages used in this study, namely Arduino IDE and Embarcadero. Arduino IDE was a programming language used to give commands to the microcontroller ESP32, while Embarcadero was a programming language for the output display of measurement results of wave height and wave direction. The microcontroller ESP32 was used by the Arduino IDE to perform programming or commands for input and output. The appearance of the Arduino IDE program is presented in Figure 8. The Arduino IDE contains everything needed to support the microcontroller, easily connect it to a computer with a USB cable or supply it with an AC to DC adapter or use a battery to start it [38][39]. Arduino IDE was software for writing microcontroller ESP32 program listings, so the microcontroller ESP32 that has been made can work according to user needs. In planning this microcontroller ESP32 software uses the C programming language which the program listing is capable to be compiled and uploaded directly to the microcontroller ESP32 using the Arduino IDE [40].

Furthermore, the display results of measuring the height and direction of the waves used in the program namely Embarcadero. Embarcadero is a software for application programming based on a

Graphical User Interface (GUI) that allows users to interface with users of the application using graphics. The Embarcadero software uses the Pascal programming language called Embarcadero Delphi [41]. This software was created by the Embarcadero company and can be used to create applications quickly and easily. Embarcadero Delphi is a programming language as well as a Software Development Kit (SDK) that can be widely used to create various applications, both desktop and mobile [42]. Delphi uses the Pascal language as an application builder. Embarcadero XE2 Delphi is a compiler as well as a programming language which is a derivative of the Pascal programming language. The Delphi compiler is very well known in the world of software developers, because of its complete facilities and supporting tools. In addition, Delphi adequately produces robust and stable applications in various fields with its RAD concept so that it can be completed quickly. The data that could be generated by this information system was made using the fast report Embarcadero XE2 [43] and generated reports of wave height and wave direction.

Figure 8. Arduino IDE used for programming of microcontroller ESP32

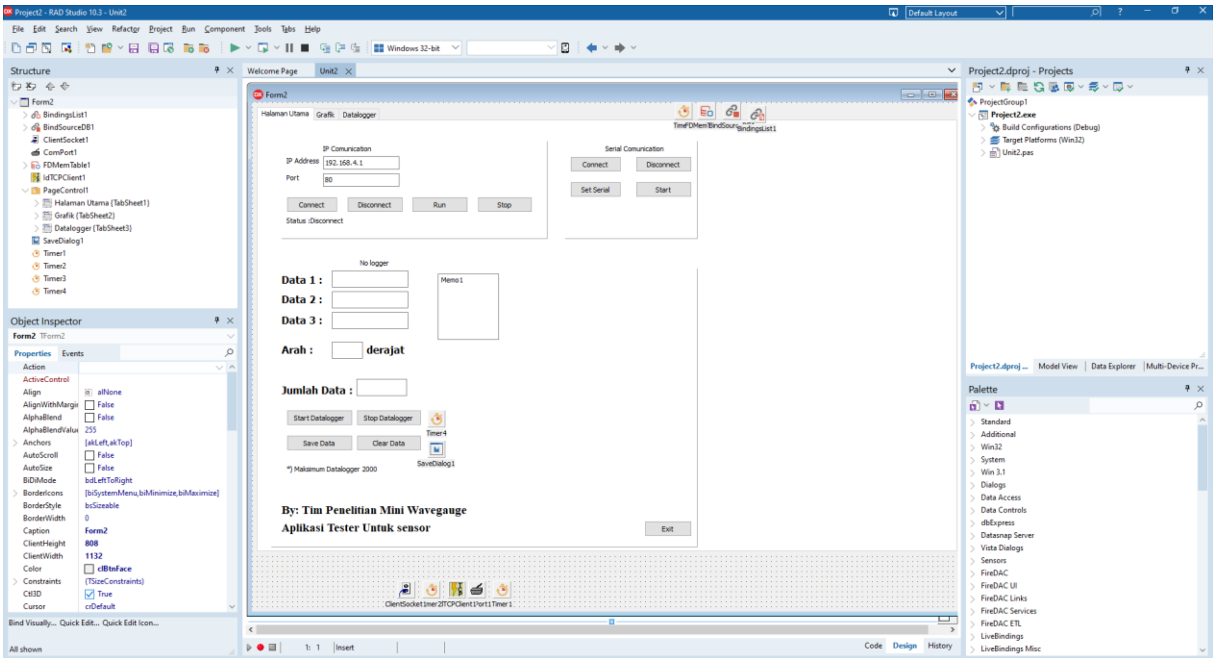


Figure 9. Display output using Embarcadero

Embarcadero has the advantage, that it can be used by multiple computers or multiuser, by using a wireless client-server network that could be accessed by anyone who had the code to run mini-wave gauge, making it more accurate and efficient, and providing convenience to its users [44]. In this study, Embarcadero produced 3 forms, namely: main page, graph, and data logger as displayed in Figure 9. On the main page, there was feature data generated, namely wave height and direction data, as well as other common function buttons such as Connect, Disconnect, Run, and Stop. The resulting wave height graphic data is displayed in Figure 10. Delphi programming by utilizing the features of the TCP/IP socket component received data from the microcontroller ESP32 over a Wi-Fi network.

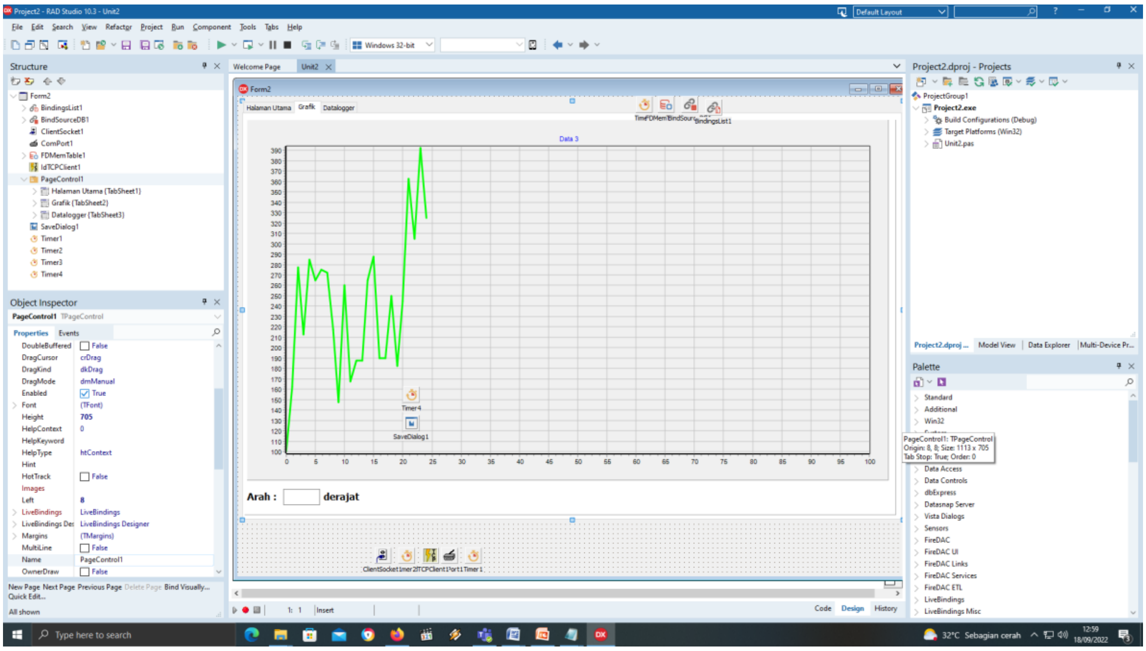


Figure 10. Example of recording wave height using mini-wave gauge

2.4 Experiment in Wave Flume

The mini-wave gauge trial in a wave flume with a size of 7.0 m in length, 0.48 m in width, and 0.7 m in height. Furthermore, this mini-wave gauge was compared with an ultrasonic fix installed in the middle of the wave flume. There were different methods used to measure the wave height from the mini-wave gauge and ultrasonic. The ultrasonic measure wave height used the Euler method, while the mini-wave gauge used the Langrage method. The basic distinct method between Euler and Lagrange was based on the context of the time rate of change within a control volume that was stationary (Euler Method) or within a control volume that was moving with the fluid (Lagrange method). This different method was implemented due to the narrowness of the wave flume. If the mini-wave gauge was in the same place as the ultrasonic, the ultrasonic would be ambiguous to measure the wave height since the ultrasonic work is based on when the ultrasonic waves reach the things then the ultrasonic waves are reflected, and it measures as the wave height recorded. And if it was implemented, there would be biases recorded in the wave height. The formula of Euler and Lagrange are shown in equations (1) and (2) based on [45] as below:

Euler equation as: $$\frac{\partial C}{\partial t} = -u.\nabla C + K\nabla^2 C + Source\ (x, y, z, t) \tag{1}$$

Lagrange equation as: $$\frac{DC}{Dt} = \frac{\partial C}{\partial t} + u.\nabla C = K\nabla^2 C + Source\ (x, y, z, t) \tag{2}$$

Remark: $\partial C/\partial t$: spatial coordinates; DC/Dt: total derivative in multi-variate calculus; $u.\nabla C$: advective flux divergence; K: diffusivity and it is constant.

3. Results and discussion

The results of wave height measurement by mini-wave gauge were then compared with the results of wave height recorded from ultrasonic sensors on a laboratory scale to see the accuracy of recording wave height data. Ultrasonic sensors are electronic devices whose ability to convert electrical energy into mechanical energy in the form of ultrasonic sound waves [46]. The workings of the ultrasonic sensor that is ultrasonic sensor detect the distance of the object by emitting ultrasonic waves and then detect the reflection. Then the sensor also emits ultrasonic waves according to the control of the microcontroller controller (Trigger pulse with a minimum t-out of 2us) (Figure 11). The ultrasonic waves propagate through the air at a speed of 344 m/s, hitting objects and reflecting the sensor [47]. In this experiment, there were different methods in data recording, such as the mini-wave gauge used the Lagrange method (fluid element moving along streamline), while the ultrasonic was used the Euler method (fluid element fixed in space) as illustrated in Figure 12. Moreover, the lack of ultrasonic, that it was only adequate to measure the wave height, while the wave direction was unable.

Figure 11. The ultrasonic sensor measures the wave height by counting the distance

(a) (b)

Figure 12. Experiment on a laboratory scale of measuring wave height by (a) ultrasonic; (b) mini-wave gauge

The waves were generated by the wave maker, on the right side of the wave flume signed by an orange board. The range of wave height recorded was -5 to 2 cm both by the ultrasonic sensor and mini-wave gauge. The result wave height recorded by the mini-wave gauge is depicted in Figure 13. Generally, the result of the wave height reading from the mini-wave gauge was smoother and could read the wave height detail until the coma value. This could be seen from the mini-wave gauge recording, the max value was 2.2cm and the min value was -4.5cm. While ultrasonic used sound waves and its accuracy was unable to read until comma values, the range wave height was shown by a max value of 2 cm and min value -5cm which is presented in Figure 14. According to this consequence, the sensor of ultrasonic was not suitable for small wave heights which had an accuracy of 1 cm [48]. Usually, the ultrasonic sensor was appropriately used for tidal measurement with high-range data [49]. Moreover, the time of recorded data, the recorded period of the mini-wave gauge was shorter than ultrasonic, represented by the data record time with the mini-wave gauge was 0.05 s, while the ultrasonic was 0.24 s for each data record. These findings showed that the accuracy of the time of the mini-wave gauge was better than the ultrasonic sensor. Furthermore, the accuracy of the mini-wave gauge was calculated using the Root Mean Square Error (RMSE) approach based on [50] using the formula of (3). The result of the RMSE calculation reached an error of 1.34 cm. Remarks: RMSE=Root Mean Square Error; A_t=wave height from mini-wave gauge; F_t= wave height from ultrasonic sensors; n=amount of data.

$$RMSE = \sqrt{\frac{\sum_{t=1}^{n}(A_t - F_t)^2}{n}} \quad (3)$$

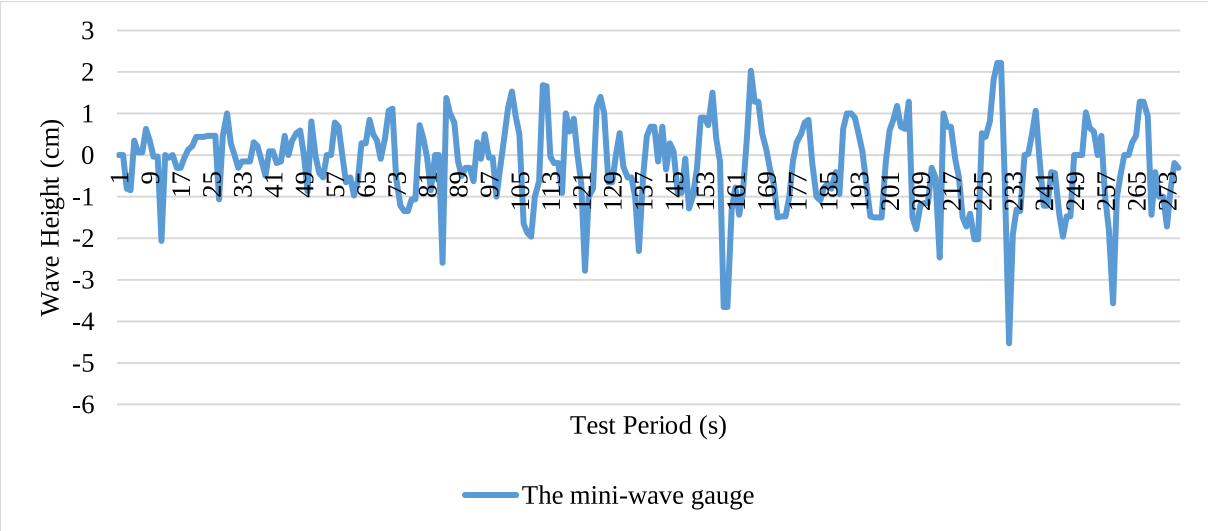


Figure 13. Wave height data recorded from the mini-wave gauge

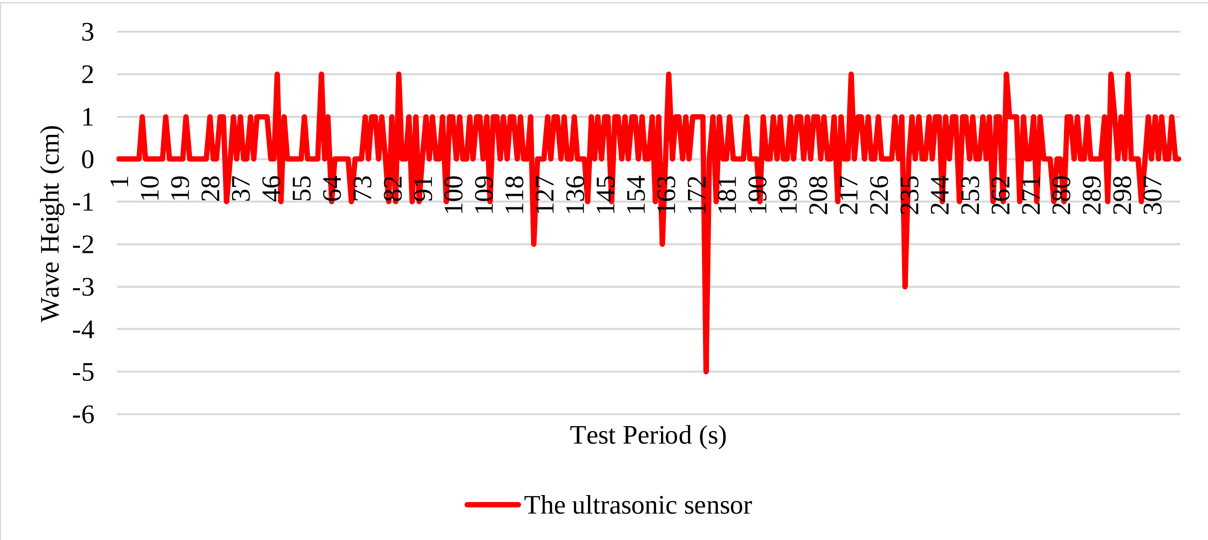


Figure 14. Wave height data recorded from the ultrasonic sensor

The comparison of wave height data recorded from the mini-wave and ultrasonic is illustrated in Figure 15. The patterns of wave height achieved were not similar due to different method data recorded, that was mini-wave gauge by the Lagrange method, while the ultrasonic used a fixed system or Euler method. However, the mini-wave gauge was quite good in wave data recorded resulting in smoother data, and the pattern fluctuates more approaching the field of wave real data.

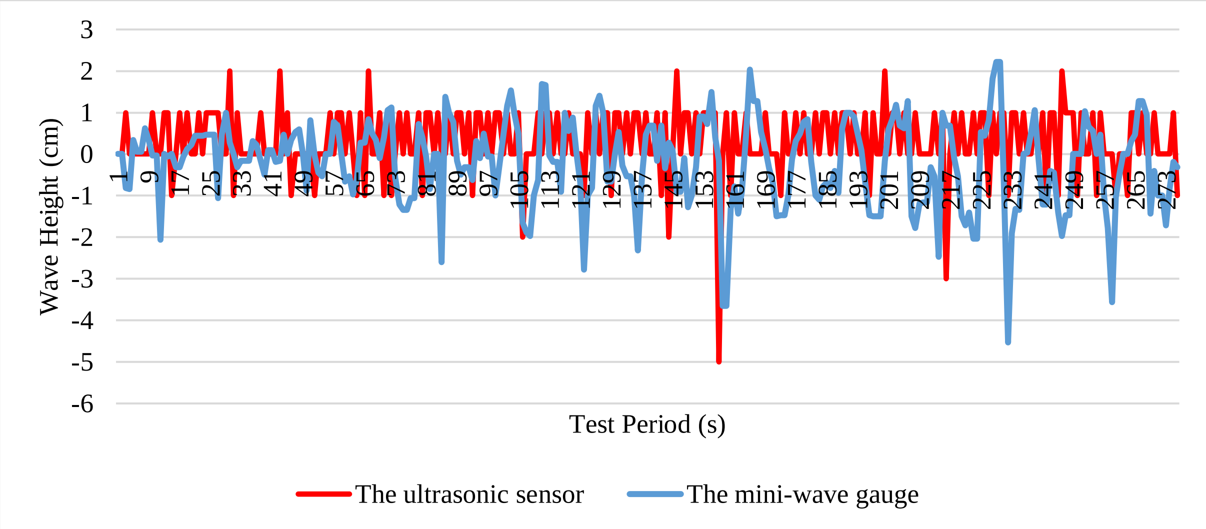


Figure 15. The comparison wave height between mini-wave (blue) and ultrasonic (red)

Due to this study still being initial research, there were still many things to be improved such as transferring data process using Wi-Fi or GSM or other methods. Packaging or wrapping of mini-wave gauge due to the security of the device, so that it did not experience leaks. Moreover, the alternative option of the power supply for sustainability is used such as solar cells or others. This research also trials the transfer of data, not only by Wi-Fi but also by the use of the Global System for Mobile Communications (GSM). However, there was a delay in data reception. The wave data received using Wi-Fi was faster in only 1 second while using GSM, there was a long time in relay data, which could be approximately 1-5 minutes, depending on the GSM signal.

4. Conclusions and suggestions

Based on a laboratory experiment, the prototype of a simple mini-wave gauge could function well and had high accuracy for recording wave height data. Moreover, the measurement of the endurance of the battery which consists of 6 units of 3.7 Volt battery, would be survived for 2 weeks of endurance. For data access using Wi-Fi, data was directly recorded every 1 second, while by using a sim card (GSM), it was recorded every 1-5 minutes, so there was a delay in data reception depending on the signal condition. Suggestion for future study, this mini-wave gauge should be trialed in the sea and verified with ADCP (Acoustic Doppler Current Profiler) to analyze the accuracy detail. Furthermore, better packaging to avoid leaks and rust, and a power supply alternative option.

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Author Contributions

Conceptualization, R.W., methodology, R.W. and A.B.P; software, A.B.P.; validation, R.W. and A.A.D.S.; formal analysis, G.H.; Investigation, R.W. and G.H; writing-original draft preparation, R.W.; writing-review and editing, A.B.P.; visualization, A.A.D.S. and G.H.; supervision, A.S.; project administration, R.W.; Funding Acquisitions, A.S. All authors have read and agreed to be published version of the manuscript.