The Design of an Arduino Based Low-Cost Ultrasonic Tide Gauge With the Internet of Things (IoT) System

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Abstract. Ocean tides play essential roles in the field of hydrography and navigation. The conventional method to measure tides is by observing the vertical variation of sea surface using a tide staff. However, this method has several disadvantages. It consumes more human resources and time to observe and record the data. Moreover, the recorded data tends to be subjective, depending on the observer. To overcome these disadvantages is by using an automatic tide gauge. This instrument can also provide almost continuous and near real-time tide data. The price of automatic tide gauge in the Indonesia market is costly. This research attempted to build a low-cost ultrasonic tide gauge by utilizing an Arduino microcontroller, ultrasonic sensor, GPS module, which is embedded with the Internet of Things (IoT) so that the real-time data can be uploaded and monitored on a webserver. The quality of the data collected from the instrument is controlled using the 3σ rule to detect and remove outliers. Moving Average and Moving Median filtering methods are applied in the system to eliminate the noise. The data accuracy-test was performed using a relative error and Root Mean Square Error (RMSE) methods. The test compares the data collected with the ultrasonic tide gauge and the direct observation method. The result shows the relative error, and RMSE values 0.226% and 6.629mm for raw data, 0.636% and 18.542mm for moving average data, 0.437% and 13.242mm for the moving median data, with the best filtering method is moving median. The instrument accuracy test results show that this instrument has excellent accuracy, with a 2,240,000 IDR instrument production budget or 7.5% of the lowest tide gauge prices.

1. Introduction

Ocean tides are a periodic phenomenon of rises and fall of sea level caused by the combined effect of the earth's rotation and the gravitational forces exerted by the moon and the sun [1]. Tidal information is essential in the world of hydrographic, navigation, and coastal and ocean engineering. Because tides vary over time, it is necessary to record the sea level variations with time information. A tide station equipped with a tide gauge instrument is needed to make accurate records and measure sea level from time to time. Measurements may ignore variations caused by waves with shorter periods in minutes. Tidal data can be used to determine a chart datum or vertical reference [2].

The conventional method to measure tides is by observing the vertical variation of sea surface using a tide staff. However, this method has several disadvantages. It consumes more human resources and time to observe and record the variation. Moreover, the recorded data tends to be subjective, depending on the observer. To overcome these disadvantages is by using an automatic tide gauge. This instrument can also provide almost continuous and near real-time tide data. The price of automatic tide gauge in the Indonesia market is costly [3]. A tide gauge's price is very high in Indonesia: around 30,000,000-95,000,000 IDR causes people to prefer observing tides using tide staff or tides station data. However,
there are weaknesses in both ways, the results of observations of the tides using the tide staff are subjective depending on the observer, and not all locations have tides stations. Based on those conditions, in this research, a low-cost automatic tide gauge will be designed, which has a minimum manufacturing budget, using an Arduino microcontroller, because Arduino is an open-source microcontroller, very cheap, and compatible with many sensors and modules [4]. Besides, this instrument also will be install with an ultrasonic sensor and a low-cost GPS module. The ultrasonic sensor gives the speed of sound on the air correction using a temperature sensor so that the distance results can be more precise. This instrument is embedded with an IoT system to store and observe data online and near real-time via web server Thingspeak. The instrument is expected to solve the high price of automatic tide gauge instruments circulating in the market by using minimum budget components and an advantage in the IoT system applied in the instrument. The ultrasonic tide gauge data will be compared with manual tides observation data recorded using tide staff to determine the instrument's accuracy. The accuracy test uses Relative Error and Root Mean Square Error (RMSE) calculation. With the accuracy test, this research's product is expected to have advantages in the minimum manufacturing cost and have an excellent accuracy performance.

2. Methodology

2.1. Time and Research Location
The location of the instrument testing is at the port of PT. Pelindo Marine Service at coordinates 7° 12' 34"S and 112° 43' 31"E, which is shown by the red arrow in Figure 1. The instrument testing was carried out for 48.5 hours, on 14 February 2020 at 7:30 PM until 16 February 2020 at 8:00 PM.

![Figure 1. Instrument Testing Location](image1)

On 18 April 2020, the instrument with GPS module has been tested on the Gribig Village field, Kudus City. The location coordinates are 6° 47' 10"S and 110° 49' 39"E, shown by the red arrow in Figure 2.

![Figure 2. GPS Module Testing Location](image2)

2.2. Tools and Materials

2.2.1. Tools. The tools used in this research include hardware and software. The hardware used is tide staff, which is used to record manual tide observation and as a mounting place for instrument sensor, so that the instrument data have the same reference as the tide staff zero value. The software used includes
instrument programming software and data processing software. The instrument programming software is Arduino IDE. And for data processing, the software is Matlab R2016a and Microsoft Excel 2013.

2.2.2. Materials. The materials used in this research include components for the manufacture of instruments consisting of a microcontroller, sensors, and modules. Microcontrollers used have the Arduino Mega 2560 Pro, the main microcontroller for tide gauge, and the WiFi NodeMCU ESP8266 microcontroller used for position measurement of the GPS module. The sensors used include the ultrasonic sensor JSN-SR04T, which functions as a sensor measuring the duration of the reflection of sound waves and a temperature sensor for fast calculation of sound propagation in the air. The data of the sound waves' reflection duration and the speed of sound can be calculated to produce distance data from the sensor to sea level. The modules used include the WiFi module to receive WiFi signals and send data to the IoT server. The RTC DS3231 module gets time data, the SD-card module backup data storage, and the Neo6mV2 GPS module gets the instrument's coordinates.

2.3. Research Stages

In this research, there are four stages needed to build an Arduino based low-cost ultrasonic tide gauge instrument.

2.3.1. Instrument Manufacturing. At the instrument manufacturing stage, several processes consist of the design of the instrument body and the electrical circuit, the arrangement of electronic components according to the electrical circuit design, creating an IoT web server, and integrating the electronic components with the instrument body.

2.3.2. Instrument Testing Stage. Instrument testing is done simultaneously with manual tides observations using tide staff. The tide staff mounted with an instrument sensor, so the instrument's data have the same reference as the tide staff observation data. The configuration used when testing the instrument is shown in Figure 3.

![Figure 3. Ultrasonic Tide Gauge Testing Configuration](image)
From Figure 3, the instrument reference synchronization to zero tide staff follows equation (1) as below:

\[ C = A - B \]  

(1)

where

- \( A \) = height of the sensor from zero tide staff
- \( B \) = distance reading from sensor
- \( C \) = tides elevation

2.3.3. Data Processing Stage. At this stage, data from the instrument will be controlled using 3\( \sigma \) rule to detect noise or outliers [5], and the data filtering performed to eliminate noise or outliers with the moving average and moving median data filtering methods.

2.3.4. Instrument Test. The instrument accuracy-test compares raw instrument data and filtering data with manual tides data by calculating the relative error and Root Mean Square Error (RMSE). The following equations are the absolute and relative error formula [6].

\[ ER = \sum_{i=1}^{n} \left( \left( \frac{|X_i - XO_i|}{X_i} \right) / n \right) \times 100% \]  

(2)

From the calculation of relative errors, we can calculate the accurate value of the measurement results with the equation:

\[ Accuracy = 100\% - ER \]  

(3)

where

- \( X_i \) = the true value or value that is considered correct in \( i \) period
- \( XO_i \) = measurement value in \( i \) period
- \( ER \) = relative error (in %)
- \( n \) = amount of data

Equation of RMSE can be seen in equation (4) [7]

\[ RMSE = \sqrt{\frac{\sum_{i=1}^{n} (O_i - A_i)^2}{n}} \]  

(4)

where

- \( O_i \) = measurement value in \( i \) period
- \( A_i \) = the true value in \( i \) period
- \( n \) = amount of data

3. Result and Discussion

3.1. Instrument Manufacturing

In this study, the main product is an Arduino based low-cost ultrasonic tide gauge instrument embed with an IoT system.

3.1.1. Electronic Component. In an instrument, electronic components are a core, which consist of comprised of microcontrollers, modules, and sensors. The design of the connections between electronic components is called an electrical circuit. The following is the design of the ultrasonic tide gauge electrical circuit instrument (Figure 4).
Figure 4 shows that the component labelled with number 1 until number 10. Number 1 is an ultrasonic sensor, which is the primary sensor in this instrument and number 2 is a temperature sensor that functions to correct the speed of sound in the air. The next number, number 3 and number 4 are a WiFi module that performs to connect WiFi signals and send data to the IoT server, and the SD-card module for data backup if the internet has problems, respectively. Number 5 is an RTC module that functions as a time information provider. Number 6 is the LCD to display sea level and time information. Number 7 is the power supply and number 8 is a microcontroller embed with a WiFi module for GPS module operation. Number 9 is a GPS module for instrument positioning. Finally, number 10 is an Arduino microcontroller that functions as the main microcontroller of the ultrasonic tide gauge.

3.1.2. Instrument Body Component. The instrument body contains two components, which is the electronic component box and a sensor arm. The electronic component box is a junction box with PVC, given an acrylic addition to the LCD cover with dimension 18cm length, 9cm width, and 8cm height (Figure 5). The sensor arm functions connect electronic components with ultrasonic sensor transducers and temperature sensors, as shown in Figure 6. This component is a PVC pipe with 60 cm length, equipped with an iron clamp mounted on a pole or tide staff.

3.1.3. Instrument Manufacturing Cost. Table 1 shows the details of the costs used in manufacturing low-cost ultrasonic tide gauges.

| Type      | Volume | Price per Unit (IDR) | Value (IDR) |
|-----------|--------|----------------------|-------------|
| Pipe Saws | 2 pieces | 30,000               | 60,000      |
| Solder    | 1 piece | 50,000               | 50,000      |
| Tide staff| 1 piece | 500,000              | 500,000     |
| Type                              | Volume    | Price per Unit (IDR) | Value (IDR) |
|----------------------------------|-----------|----------------------|-------------|
| Iron Clamps Welding Services     | 2 pieces  | 20,000               | 40,000      |
| Acrylic Cutting Services         | 10cm²     | 2,200                | 22,000      |
| PVC pipe ¾                       | 2 meters  | 10,000               | 20,000      |
| glue gun                         | 5 pieces  | 2,000                | 10,000      |
| Glue G.                          | 5 pieces  | 6,000                | 30,000      |
| JSN SR-04T Ultrasonic Sensor     | 1 piece   | 150,000              | 150,000     |
| Arduino Mega 2560 Pro            | 2 pieces  | 300,000              | 300,000     |
| LCD module 1602                  | 1 piece   | 50,000               | 50,000      |
| DS3231 RTC Module                | 1 piece   | 50,000               | 50,000      |
| SD-Card Module                   | 1 piece   | 50,000               | 50,000      |
| WiFi Module ESP-8266             | 1 piece   | 60,000               | 60,000      |
| DHT22 temperature sensor         | 1 piece   | 50,000               | 50,000      |
| 9V DC adaptor                    | 1 piece   | 100,000              | 100,000     |
| Node MCU ESP8266                 | 1 piece   | 90,000               | 90,000      |
| NEO-6MV2 GPS Module              | 1 piece   | 68,000               | 68,000      |
| Cable connector                  | 30 pieces | 3,000                | 90,000      |
| Junction box                     | 1 piece   | 200,000              | 200,000     |
| Solder wire                      | 2 roll    | 25,000               | 50,000      |
| Services fee                     | 2 days    | 100,000              | 200,000     |
| **Total cost**                   |           |                      | **2,240,000**|
3.2. Instrument Testing Result
Tides data and coordinates from the instruments are recorded on the thingspeak server and SD-card (Figure 7). In the thingspeak server, there are 9209 recorded data, with an interval of 15-19 seconds. Because this instrument relies on WiFi sourced from mobile hotspots to send data to the thingspeak server, many data have a delay of recording up to several minutes (Figure 8).

![Figure 7. Tides data in the thingspeak server](image1)

![Figure 8. Delay on data recording](image2)

Because the data storage system on this instrument not only relies on the thingspeak server but also uses an SD-Card, all unrecorded data due to delay has been recorded on the SD-Card. The amount of data recorded on the SD-Card is 9621, 412 more data than the thingspeak server (Figure 9).

![Figure 9. The SD-Card tides data graph](image3)

Figure 9 shows the tides data generated by this instrument contains some noise or outliers. The noise demonstrated in number 1 occurs because there is an object blocking the ultrasonic sensor. The number 2 is the noise that occurs because of the disconnected cable due to heat, and the value is zero (0).

3.3. Data Quality Control
The instrument’s tide data will be controlled using three sigma’s (3σ) rule to determine the instrument’s precision level. Table 2 describes the results of data quality control calculations.
Table 2. Data quality control

| Data          | Data Passed | Data Failed | Passed (%) | Failed (%) |
|---------------|-------------|-------------|------------|------------|
| First 24 hours| 4714        | 75          | 98.434     | 1.566      |
| Second 24 hours| 4832       | 0           | 100        | 0          |

Table 2 shows that most data from the ultrasonic tide gauge instrument passed from data quality control calculations. However, 75 data failed in the first 24-hour data sample were outliers with a zero value (0) caused by the disconnection of the connector cable on the sensor.

3.4. Tides Data Filtering
The moving average and the moving median are used to filter tidal data observation. Figure 10 shows the result of tidal data filtering.

Figure 10. Data Filtering Graph

3.5. Instrument Accuracy Test
Data from the instrument will be calculated relative to errors to determine the instrument's accuracy and RMSE calculation to resolve the instrument readings' error. Filtered tidal observation data (Figure 10) compare with tidal staff data to determine the relative error and RMSE (Table 3).

Table 3. Result of Relative Errors and RMSE Calculation

| Data            | Relative Error (%) | Accuracy (%) | RMSE (mm) |
|-----------------|--------------------|--------------|-----------|
| Raw data        | 0.226              | 99.774       | 6.629     |
| Moving average  | 0.636              | 99.364       | 18.542    |
| Moving median   | 0.437              | 99.563       | 13.242    |

4. Conclusions
In this research, a low-cost ultrasonic tide gauge instrument was created, which has Rp. 2,240,000 or only 7.5% of the lowest tide gauge prices on the market. The low-cost ultrasonic tide gauge's quality test results shows the relative error, and RMSE values 0.226% and 6.629mm for raw data, 0.636% and
18.542mm for moving average data, 0.437% and 13.242mm for the moving median data, with the best filtering method is Moving Median. However, this low-cost ultrasonic tide gauge instrument still has some problems, the first problem is a noise caused by an object blocking the sensor, sensor quality, and technical faults such as disconnected connector cables, and the second problem is delay while recording the data, but it can be solved using good internet connection.

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