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ORIGINAL PAPER

Development of autonomous multi-sensor ocean monitoring instrument designed for complex archipelagic waters

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Abstract

This paper presents the development of low-cost multi-sensor ocean monitoring instrument to measure oceanographic parameters. The aim of this instrument is to fulfil the monitoring specifically for archipelagic countries with complex waters, and it allows for both vertical and horizontal measurements. The platform contains removable sensors, rechargeable batteries, satellite system, and micro-controller. Inside the instrument, the probes are primarily to measure acidity level (pH), water temperature (°C), salinity (ppt), conductivity (ms/cm), turbidity (NTU), and depth (m). Furthermore, data are stored in an internal SD card and simultaneously transmitted to a website portal data via satellite after it goes to the surface water. For validation, several tests had been conducted in controlled laboratory conditions and field setting, in which the test results had shown satisfactory results. In the future, the system will be upgraded by adding extra units of antenna, chlorophyll sensors, and a power changer made from thrusters. Currently, this instrument is operational and available for use in archipelagic countries with dynamics depth.

Keywords Ocean database · Autonomous instrument · Drifter trajectory · Sensor probe · Archipelagic countries · Ocean observation

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Introduction

Ocean monitoring is strictly dependent on the proper methodologies and the developments of new sensors and platforms (Pearlman et al. 2019; Purba et al. 2017). As the ocean is a very complex system due to the interaction between land and atmosphere, continuous monitoring is needed to further understand ocean dynamics (Weller et al. 2019). Direct sampling combined with satellite transfer data in oceanographic studies was developed in the last decade. These methodologies are essential for academic and research quality improvement (Marcelli et al. 2014; Révelard et al. 2022). Understanding dynamic changes of the oceanic and atmospheric environment is a key in predicting future conditions such as ecosystem health (Albaladejo et al. 2012), climate change, and other ocean processes. In the end, this monitoring data becomes a guide to the government's policy-making process (Lockridge et al. 2016; Ormston et al. 2014; Révelard et al. 2022).

Revolution in ocean observing technology to monitor ocean condition began in the last decade (Whitt et al. 2020). Recently, development of observing platforms such as autonomous instruments with complete sensors has grown rapidly. The introduction of new technology concept enables more effective ways of oceanographic measurement to observe and monitor the ocean. High precision data system is key in regularly monitoring oceanic conditions in the era of climate changes (Lo Bue et al. 2021). However, there is a paucity of in situ data attributed to the logistical requirements for field surveys, limited agencies that focus on marine observation, and the overall complexity of natural ocean characteristics (Gerin et al. 2018). Moreover, continuously observing the ocean dynamics means continuous improvement on instrumentation capacities, e.g. accuracy, precision and resolution, to maintain the quality control and precision of the instruments manufacturing. These schematic processes will lead to high-quality observational data.

Ocean observation by autonomous instruments method could transfer a large amount of near real-time data. Meanwhile, nowadays the use of low-cost instrumentation from ships is gaining more and more attention (Callies et al. 2021; Marcelli et al. 2014). This instrumentation makes it possible to reduce the costs of field surveys and, at the same time, improve the spatio-temporal coverage of oceanographic data (Kröger et al. 2009; Purba et al. 2017).

In this study, we have developed a monitoring instrument called ARHEA (advanced drifter gps oceanography coverage area). It is a type of autonomous ocean vehicle (AOV), which is an improvement of a previous version of technology called RHEA (Purba et al. 2017). It was designed with practical and user-friendly scheme that aims to accumulate novel information of monitoring ocean characteristics with a real-time data system. Simulations were performed via site measurements and data analysis, providing engineering solutions through laboratory tasks.

The ARHEA is expected to provide a solution to the sampling problems with applicable technology and suitable data system in archipelagic countries. In this area, the complexity of bathymetry, circulation, and biodiversity is unique. Besides, oceanographic data is crucial to predict potential fishing grounds and illegal fishing activities (Khan et al. 2020; Purba et al. 2020) and to understand the marine ecosystems, biogeochemical process, and habitat (Kröger et al. 2009).

The idea for a new observation instrument began in 2017, and the development of this instrument started in 2019. It took two years from designing to sea-testing including synchronized with the portal data. In this process, development

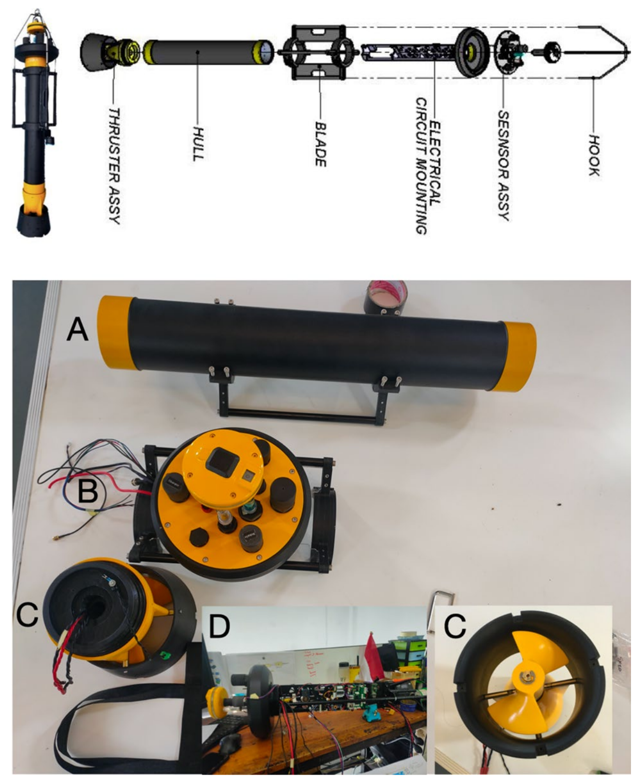

Fig. 1 Design architecture and instrument part. Photographs of ARHEA, unassembled components: **A** main housing, **B** sensors, **C** thruster, **D** micro-controller (top) and once assembled (bottom)

of the systems was done by collaboration between Marine and Technology Laboratory, University of Padjadjaran and underwater technology industry in Bandung, Indonesia. The design and assembly were done in Bandung, while field test in several locations including Pulau Seribu, Pangandaraan bay, and Bandung (pool simulation) (Fig. 1).

Materials and methods

Instrument design and framework

ARHEA is an advanced version of RHEA instrument, whose primary function is to measure oceanographic parameters. The name Rhea comes from the name of a goddess in Greek mythology; the Titaness daughter of the earth goddess, Gaia. This earlier instrument only floats on the surface of water, while the improved version has

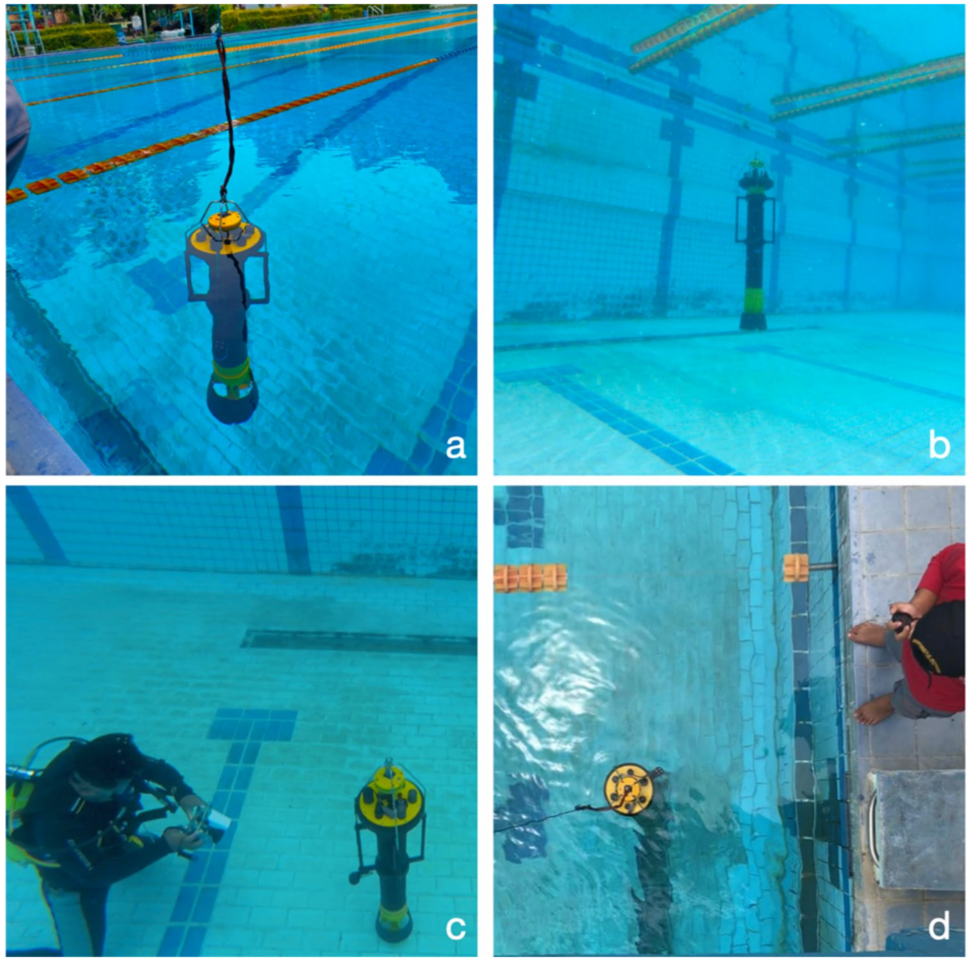

Fig. 2 Pool test experiment, **a** buoyancy test in the surface, **b** ARHEA in the water column, **c** in the bottom, **d** measuring speed in one cycle

new design and more functions (Purba et al. 2017). The ARHEA hull is designed to achieve maximum function, stability, and easy to carry. Its design is inspired by the shape of the mangrove propagule and its floating system (Fig. 2), and thus the design is tube-shaped and elongated. Besides being easy to carry, lightweight, and easy to use, it is integrated with information systems. This newer instrument is also operated easily and can be carried by two or three persons, including technicians.

The main goal of developing this instrument is to provide enhanced delayed and near real-time data. ARHEA is expected to be a cost-effective option suitable for open and shallow water, representing archipelago countries. The instrument is equipped with sensors that are supported with batteries for the operational system. The electronic system function can read electrical signals received from marine sensors and translate them into physic values, accommodate data storage in digital media, and transmit data in near real-time or using RF telemetry devices. This instrument is used to measure oceanographic parameters vertically to the bottom of the water. This instrument is either used by submersion or drifting on the water surface. The data retrieve is then sent and stored in the data portal website (https://isea-podc.org). This portal developed to receive data from many observation instruments and researchers (Faizal et al. 2021). Data (near real time) is sent by iridium satellite to server in Padjadjaran University. The raw data is then displayed in the website and also sent to regional experts to analyse. The process in the experts is to handle bias data, process quality data,

Table 1 Specification of sensors embedded in the system

Sensor	Type	Max depth (m)	Precision
pH meter	SKU SEN0161	NA	± 0.1pH (0–14pH)
DO meter	SKU: SEN0237-A	30	0 ~ 20 mg/L
Turbidity	SKU SEN0189	100	0– ± 1000 NTU
Temperature sensor	SKU: DFR0198	300	± 0.5 °C (− 10 °C to + 85 °C)
Conductivity meter	SKU: DFR0300-H	NA	10 ~ 100 ms/cm
Pressure sensor	SKU SEN0257	290	0.5%(0 ~ 150 m)
Altimeter	SKU SEN0226	500	± 1 m (± 500 m above/below sea level)

and give a preliminary information. Furthermore, the delayed was data also displayed in the portal data website. The users can choose raw data or delayed data for their research or purpose.

Sensors, calibration, and main tests

ARHEA is designed to be modular while carrying multiple sensors. Thus, it is crucial to choose suitable sensors, and several considerations must be taken, such as applicable packaging and response time (Auraen 2019). In this project, our challenge was to find sensors that can tolerate pressure more than 100 m. Sensors were purchased online from various international and national manufacturers. Currently, the installed sensors detect acidic level (pH), turbidity, temperature, conductivity, and dissolved oxygen (Table 1). Most of the aforementioned sensors can withstand certain depths.

These sensors were then modified to fit into the cables to fit the size of the tube. Then, they were connected to microcontrollers, batteries, satellite transmitters, and data storage. To manage the sensor's power needs, the power supply was increased to above 100 A, and rechargeable by one charger connection from the outside, and the cells were balanced by setting them as parallel. The sensors were mounted on the top of the hull and glued on the device’s side to avoid the entry of water into the tube.

For validation, laboratory tests had been conducted. Vacuum test was done to check the presence of leaks in the tube, especially those seen on the top cover, including sensors hole and bottom cover. Data from sensors were then compared to portable tools and laboratory analysis results. Physico-chemical test was conducted using a standard solution and untreated seawater. The parameters tested were: (1) pH parameters using two instruments: Meher Toledo and Lutron 207; (2) Dissolved Oxygen Parameters using one instrument, namely Lutron PDO 519; (3) Salinity Parameters instrument, namely SKU121471. For durability and usability, a series of tests had been conducted on the ARHEA, whose gathered data were then compared to those of other available software. Design endurance test was done using Software Ansys, while leakage test was done using a vacuum machine. Telecommunication system and data transmission were tested using rockblock system and telemetry. Lastly, buoyancy, battery life, and GPS position had been validated. Field trials were conducted in a pond and at sea. All the tests were conducted periodically and structured to check the performance of the tool. The documented results served as evaluation material.

Results and discussion

Instrument design and characteristics

The ARHEA instrument generally consists of six basic parts. It has a hook, located at the top side, and a propeller at the bottom. The hook and anchor line at the hull will be used when measuring a specific method site. This instrument is constructed from aluminium alloy, has a high draft, and has a housing that is slightly negatively buoyant (Fig. 1). All materials used are waterproof. ARHEA's body is tube-shape and shall be placed vertically to maximize downward thrust.

Table 2 Instrument characteristic

No	Instrument description	Remarks
1	Length	1.3 m
2	Weigh in the air	~ 15 kg
3	Diameter	26 cm
4	Communication	Iridium satellite
5	Navigation	GPS (Global Positioning System)
6	Body material	Aluminium alloy 2024

This instrument also has a static external bladder, allowing it to move efficiently in the water column. The depth sensor is placed at the open space side. The depth of the waters that can be reached is about 180 m based on the test results.

The main housing is comprised of four main subsystems: (1) sensors, which measure ocean parameters, (2) microcontroller that manages function control and scheduling, (3) a data transmission system via satellite that controls communication, and (4) batteries and cables. To prevent this device from fully sinking to the ocean floor, the platform will use the buoyancy principle when descending and use thrusters when ascending to the surface of the water. At the top near the sensor position, there is also a light indicator to indicate if all systems are ready and the instrument is ready to be deployed.

Compared with RHEA which has a height of 1 m, this new instrument has a height of almost 1.3 m. This is due to the addition of thrusters at the bottom and a hook at the top. In addition, changes are made to the placement of sensors, where ARHEA has sensors located on top. This modification is due to the thrusters already at the bottom. For data transfer, an iridium satellite is embedded in the system. This kind of data delivery system is already used in Argo float (Thomson and Emery 2014). Due to high cost of delivery data transfer, there is also a memory card to save the data (Table 2). This data can be transferred manually to laptop or computer. The ARHEA has weight in air of about 15 kg. In comparison, Argo float instrument weighs about 25 kg (Schmid et al. 2007).

Laboratory and field test

Vacuum test results showed that the housing did not obtain deformation values that might interfere with the overall

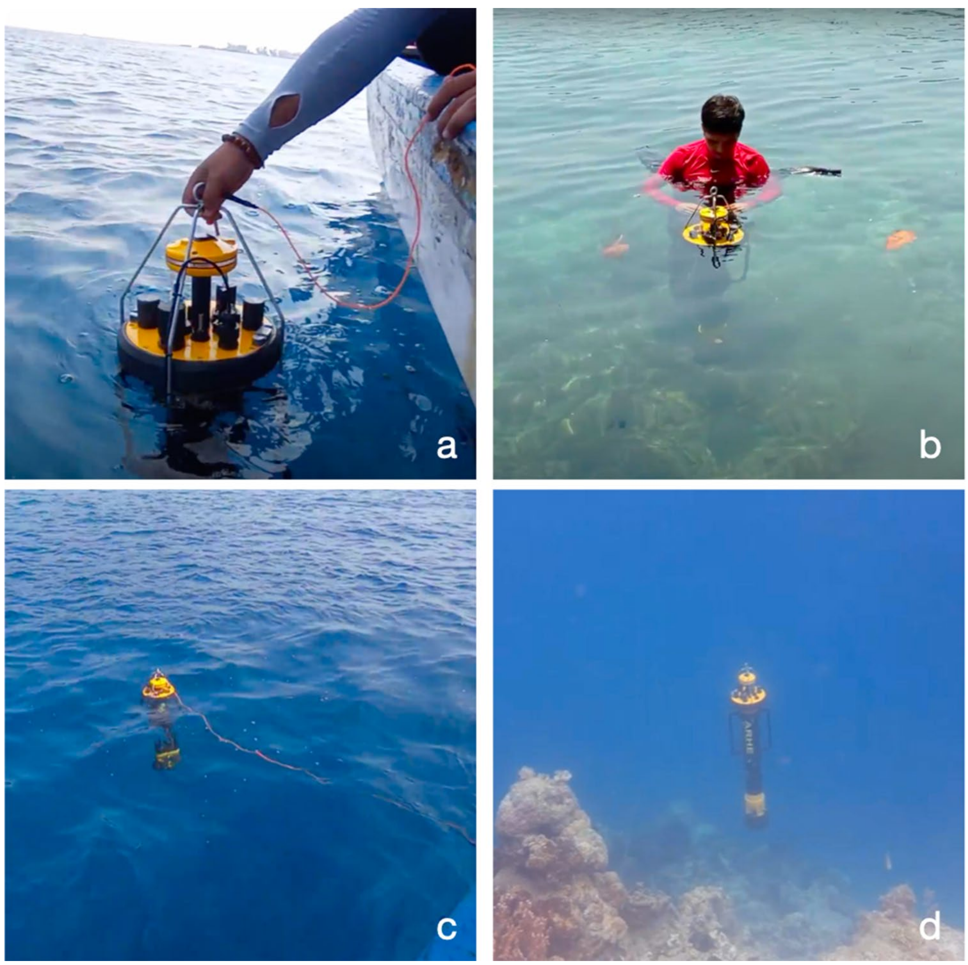

Fig. 3 Sea trial in water in the Pramuka island, **a** deployment, **b** buoyancy test, **c** on the surface to transmit data, **d** in the coral reef area

function of the tool or with component interaction in the design. Maximum deformation was obtained from the middle of the lid with a value of 0.015 mm. The contours of the safety factor would indicate possible failure of a specific part or the entire geometry structure. The analysis of the value of safety factors on the model tested showed satisfactory results with a minimum safety factor value of 1808. This means the model will fail at a depth of 1808 times greater than the depth of operation. In the case of this maximum deformation, the expected affected component is only the sensors that are attached to the lid. From the test, the sensors were not disturbed by the deformation. Furthermore, in tests conducted on battery power, propellers consume the most power.

Field testing of the ARHEA was divided into two steps: pool test and sea test. The field test was coordinated by the Marine Research Laboratory (MEAL) of Universitas Padjadjaran and PT Robomarine Indonesia (RMI). Pool tests were conducted on 15 and 19 March and April 23, 2021, in Bandung. The tests were repeated three times, with the duration of four to five hours per day, under maximum depth of 5 m. During the pool tests, a series of on-site validation was carried out. Floating test was also carried out to determine optimum buoyancy. This test is done by floating ARHEA on the surface and observing at its balance, distance from the surface of the water with the sensor, and stability during surface. Other tests included power consumption and performance (propeller thrust test), battery endurance, and telecommunications system (Fig. 3).

Prior to deployment, several settings were calibrated through connecting the instrument to the computer. Indicator lights installed at the top were visually checked. Ideally, the instrument should exhibit positive buoyancy so that the sensors could rise above the waterline during surface intervals. Adjustments were made by adding weights of 100 and 200 g to keep the sensors vertical, aligning the sensors perfectly when sinking. Further down speed tests were conducted with several thruster power change attempts; In 2 meters depth simulation, for the power of 150 volts, the ARHEA sink in 15 seconds, while in 300 volts, it sinks in 4 seconds. As a comparison, an Argo float takes around 0.08 m/s to descend and ascend (Schmid et al. 2007). System testing and data telecommunication system via satellite were running well. Data was sent to the data portal and emailed in.txt format; however, there was delay of data reception about 10–15 min, after the instrument appeared in the surface. The data stored in the memory card were downloaded and successfully viewed. In this test, there were many data errors, since the sensors did not show the proper values for freshwater. In general, the pool tests were considered successful and critical adjustments were done to prior to at-sea deployment.

The sea test was carried out on 26–29 April 2021 on Pramuka Island, Pulau Seribu, DKI Jakarta (5.744558° S, 106.611579° S, 106.611579° E). The site was due to the favorable waters and ocean current conditions for conducting experiments, and the availability of adequate infrastructure for hardware or system troubleshooting. First, the GPS of the instrument was evaluated. GPS location recording by the ARHEA were compared to handheld GPS (Garmin®) values. The results showed that the GPS device in the instrument had about 5–15 m accuracy.

For the pool test and sea trial, several modifications of buoyancy had been made, by adding weights so that optimum buoyancy could be achieved. The addition of this ballast was due to the disruption of the water column so that ARHEA would not fully sink. This resulted in the sensors not sinking completely. Water physic conditions such as temperature and salinity will affect the density of water. This will cause change in buoyancy (Purba and Pranowo 2015). The evaluation data transfer shows that data acceptance is still an obstacle. This occurred in field tests where data was not received multiple times by the data portal. This problem might be due to the lack of antennas to send the data. Additional antenna was also used in Argo float and other ocean instrument (Carlson et al. 2019; Roemmich et al. 1998). The mounted antenna was attached directly so that seawater would still touch the sensor at the time of data transmission, hence may be one of the shipping constraints.

Next, ARHEA was deployed using a small vessels and near the harbour. The instrument was deployed at a depth of about 5–30 m. In both tests, the strap remained attached to the instrument hook to prevent the loss of the instrument. Before being deployed, several settings had been adjusted, including thruster velocity, signal processing, and buoyancy. Immediately when the signal was obtained, the instrument was deployed. To observe the stability and performance of the device in the water including deep sensor, two divers participated in monitoring the device (Fig. 3).

Buoyancy was still a challenge during the first test. Waves affected the instrument, but this was solved by adding 100–200 g of ballast. The duration of testing was varied every day to cope with different prevailing ocean currents and tidal conditions. Test on the first day was carried out for two hours (13:00–15:00 WIB), then on the second day, was

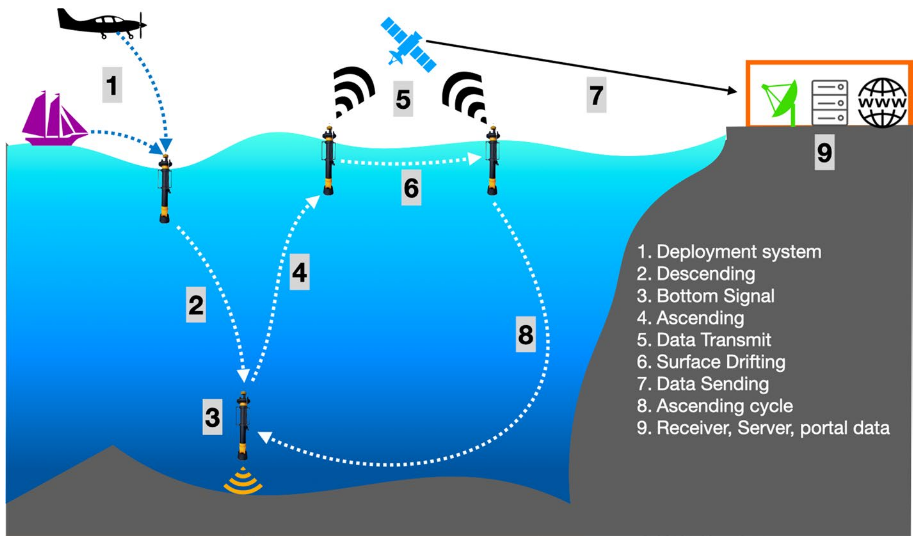

Fig. 4 A systematic process of ARHEA, (1) deployment from ship or plane, (2) descending to the water column and measuring parameters, (3) reaching maximum depth by using an acoustic sensor, (4) ascending to the surface, (5) sending data to the satellite, (6) surface drifting, (7) sending data to the server, data being archived, and published in portal data

Table 3 Data from sensors

Parameters	Min		Max		Lab. analysis
	ARHEA	Portable instrument	ARHEA	Portable instrument	
Temperature	29.41	27.65	32.01	32.90	30.34
pH	6.72	6.10	8.89	8.25	8.34
Dis. Oxygen	6.29	4.80	8.20	5.90	4.65
Salinity	31.2	31.7	33.2	32.8	32.5
Turbidity		NA		NA	

run for 8 h (07:00–15: 00 WIB), and on the third day for 4 h (08:00–11:00 WIB). The data taken were temperature, salinity, pH levels, turbidity, and dissolved oxygen levels. Data logging interval on ARHEA was performed for 30 s during dive mode. The amount of data recorded every single day was different. The number of data recorded on the first day was 13, while on the second day, there were 249 data, and on the third day, there were 58 data. Average data is presented in Table 1.

The depth sensor mounted next to the blade worked properly. It was visible at a distance from the seabed about 1–2 m before returning to the surface. Experiments were conducted with seabed characteristics of sandy, rocky, and coral reef ecosystems. The trial was also conducted with variation of slope characteristics. From the measurement in the pool, this issue was solved when conducting the sea trial. The temperature in the north-western part of Java including Pulau Seribu is about 28.5–30.5 °C, and salinity has a value of 30.5–32 psu (Siregar et al. 2017). To be scientifically used, some recommendations for temperature accuracy are 0.002 °C and 0.01 PSU for salinity (Wong et al. 2020).

Data integration

The ARHEA has been successfully developed to measure oceanographic parameters vertically. The operation for this instrument is by deploying it in the open ocean to continuously acquire of water quality data such as temperature, salinity, dissolved oxygen, turbidity, and conductivity. In general, ARHEA can be deployed via aircraft and ships. Before deployment, it is imperative that the indicator would light up. As it sinks to the bottom of the water, and then rises up to the surface, measurements of parameters are carried out continuously. ARHEA will send data to the satellite once it reaches the surface. It takes 10–25 min to send data in one cycle. When the instrument is on the surface, it drifts but still performs measurements. Before diving to the bottom of the water, the data is sent to the satellite to be transferred to the server again. In the end, the instrument then descends back to perform measurements (Fig. 4).

Data from ARHEA will be collected and sent automatically to the website (www.isea-podc.org). This data portal is currently being developed to receive more data from many sources; displayed as both raw and validated data. Data collection by sensors can be arranged according to the needs of researchers. During experiments in the pool as well as at sea, the data measurement time ranged from 1 to 10 min, to determine the cost of sending data via satellite (Table 3).

Conclusion and future work

In general, the data generated by this instrument indeed has some biases but within tolerable range. This is probably due to sensors having low level of accuracy and precision, or there were mistakes in conversion of values from voltage. To maintain good data quality, regular checks on sensors are always carried out which is done once a month if this instrument is not used. The inspection is carried out by looking at the resulting data, the level of precision compared against high accuracy instruments, and checking the cables. Last, the performance of the whole systems is evaluated in laboratory, shipboard, and pool simulations.

Therefore, in the future, it is expected to validate with more precise sensors. This will have certainly impact the cost of purchasing sensors. Usually, the better the precision, the higher the price will be. In this study, replacing the sensor with a better one was not a problem because, from the beginning, the experiment needed to consider the most suitable sensor for use. ARHEA is a marine instrument that is highly important for monitoring the ocean. The next step in development of this instrument is deployment in Indonesia and other archipelagic countries since these areas are the most vulnerable to global climate impacts. However, ARHEA is still not perfect, and thus its efficiency will be constantly improved. There are some technical issues that need to be addressed for it to be fully functional in the ocean. With this global measurement, it is expected that challenges in the marine environment can be solved. The ocean itself plays an important role in the global climate system, especially in complex oceanic regions. With continuous and precise ocean data gathering, challenges such as climate change and fishing zones can be identified and predicted. Experiments conducted in ponds and the ocean have shown that this instrument can be used in actual waters. With the ever advancing ocean technology, there is still the challenge to build less expensive instrumentation.

In terms of shortcoming, the resolution of gathered data is a major concern and should significantly be improved to increase the accuracy and precision of the instrument. Besides, the thruster consumes a lot of energy and depletes the stored energy. An alternative solution is to use a pump system similar to the embedded component of the Argo float instruments (Roemmich et al. 2019). It is more efficient in power usage and cheaper. In the future, the addition of antennas should garner near real-time data. The next plan also consists of installing a chlorophyll-a sensor. This sensor is crucial in the marine field, since chlorophyll-a is a proxy for water productivity measurement (Kröger et al. 2009). The territorial waters of the archipelago, especially those in the tropics, have high chlorophyll-a fluctuations due to the influence of monsoons and rivers. There is still one sensor hole in this instrument that can be utilized, making it possible to add a chlorophyll-a sensor. Lastly, improvements should be made to construct a robust instrument that requires little maintenance and easy routine re-calibration. For application in archipelago countries, the issue of short battery life does not seem to be a real obstacle since depth and coverage area is small. In addition, improvement by adding additional batteries pack is possible.

Another improvement to the ARHEA is that its Technology Readiness Level (TRL) can be increased to Level 9. Based on self-assessment, this instrument is still at TRL 7. In order to reach level 9, several points are required: (1) repeated tests conducted at sea and (2) the existence of technology audits from professional institutions.

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Data availability All data used are openly available, and relevant websites are mentioned.

Declarations

Conflict of interest The author declares that they do not have conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by the author.

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