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Design of Remotely Operated Underwater Vehicle (ROUV) for Underwater Metal Detection

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Abstract

The underwater surveys and inspections in Indonesia were carried out mostly by the operation of practical divers who were limited to shallow waters. The deep - sea exploration requires more advanced technology. The development of underwater technology is required to support many functions of underwater surveys and inspections. The purpose of this study was to design a Remotely Operated Underwater Vehicle (ROUV) for detecting objects with metallic materials. The ROV was designed with a Penta Tubular model and camera assistance for navigation, the JSNSR04T ultrasonic sensor to detect object distances, and the LJ12A3 inductive proximity sensor as a metal detector. ROUV rides are controlled using a keyboard with certain keywords and monitored using a smartphone. Testing the JSN-SR04T Ultrasonic sensor uses 5 variations of distance, namely 20cm, 40cm, 60cm, 80cm, and 100cm, with the detection object in the form of a plate with dimensions of 35cm x 35cm. For testing the inductive proximity sensor, the LJ12A3 type uses 3 variations of materials, namely steel plate, aluminum plates as metal objects, and PVC plates as control materials. Tests were carried out in two mediums, namely in air and underwater. Based on the results of data retrieval testing of the ultrasonic distance sensor in the air, the smallest error percentage is 0.06%, and the highest error percentage is 0.705%. In the underwater test, the error percentage was 0.49% for a distance variation of 100 cm. The ultrasonic distance sensor type JSN-SR04 cannot read distance data below 89.75 cm in water due to differences in the speed of sound propagation in different media. The Inductive Proximity Sensor can work well in air and water mediums with 100% accuracy on steel plates, aluminum plates, and PVC plates.

1. Introduction

The underwater surveys and inspections in Indonesian water were carried out mostly by the operation of practical divers that limited to shallow waters. The development of underwater technology is urgently needed to support various survey and inspection activities such as submarine hull inspection, seabed inspection, underwater welding, subsea pipeline inspection, and works carried out in places that cannot be reached by humans. These survey and inspection activities can be assisted by high-tech underwater equipment such as Remotely Operated Underwater Vehicles (ROUV). ROUV is an underwater vehicle that is physically connected and controlled by an operator who is on a ship above the surface of the water [1]. This robot-like machine allows the operator to drive it from a relatively safe, dry, and comfortable place such as on a boat or platform located on the surface of the water above the ROUV.

ROUV can be classified as an unmanned submersible robot that is moored, uninhabited, highly maneuverable, and operated by an operator. ROUV is essential as an underwater robot that allows the operator to stay in a comfortable environment while the ROUV is working in a hazardous environment [2]. ROUV operations as an underwater vehicle rely heavily on the ability to process motion, both vertical motion (floating, drifting, and sinking), horizontal motion (forward, backward to right or left laterally), and diagonal motion (drifting forward to the right/left or up/down). The ability to process motion is largely determined by the buoyancy force of an object in water. The ability of an object to float in a fluid is a general definition of buoyancy force, this force depends on the density of the fluid and the volume of the object, but not on the composition or shape of the object, and its magnitude is equal to the weight of the fluid displaced by the object [3]. For homogeneous objects (all the constituent particles of the object are similar) with a symmetrical shape, the weight point of the object has the same location as the center of mass of the object [4].

There are several problems in ROUV operation [2] such as control system, under-actuated conditions, how to recover poses/station keeping, and how to communicate between ROUV vehicles and controllers. ROUV systems are very complicated mainly due to non-linear hydrodynamic effects, parameter uncertainty, and lack of dynamic models and ROUV parameters. Conventional controllers cannot compensate for unmodeled vehicle hydrodynamic forces or unknown disturbances. An under-actuated condition is defined as a condition that has less control input than a degree of freedom, so the ROUV will be very difficult to maintain at a point or at a certain depth. In addition, issues of the ROUV sub-system, size, weight, payload, motor, and operating depth, as well as the inability of wireless communication systems to transmit video streams even over short distances, are decisive in ROUV design.

The ROUV control system in general can be divided into Open-Loop and Closed-Loop. The Open-Loop control system sends a command to generate multiple actions for the actual condition to be the desired state, but this control system does not verify whether the action occurred or whether the action corresponds to the desired condition or outcome [5] Whereas, the Closed-Loop control system monitors the actual conditions generated and inputs feedback information back into the control process, this information is then compared with the desired conditions to verify the conditions that have been achieved [6]. In its application, microcontrollers are used in products or devices that are controlled automatically such as car engine control systems, remote controls, production machine controllers, and so on [7]. The use of drive with brushless motors is very popular among operators of radio-controlled aircraft due to their power efficiency, long service life, and lightweight compared to traditional motor brushes. The brushless DC motor controller is much more complicated than the brush motor controller [8].

Research conducted by Prüf [9] discusses how to detect metal in underwater conditions, by using a metal detector as an underwater metal detector. The pulse induction (PI) method works with the principle of electromagnetic echoes, where magnetic fields are able to induce currents in metal objects and display it in an indicator. For underwater operation, large gate times are needed to overcome the attenuation of effects due to low conductivity underwater. Research conducted by Passeraub [10] explains that an inductive proximity sensor is a sensor that is widely used for contactless measurements in various products and systems such as robots, assembly lines, telecommunication, or security. The measurement range of the inductive proximity sensor is between of 0.1 to 5 cm, for example, used in Application Specific Integrated Circuits (ASIC). Research conducted by Saragih et al [11], developed a wireless distance measurement instrument based on Arduino Uno Atmega microcontroller and HCR-04 type ultrasonic sensor. The research was conducted to replace conventional distance measuring instruments that can only be used for reachable places. The result of Saragih′s research show that the HCSR-04 ultrasonic sensor can be used at many distance variations with 100% accuracy for 60 cm distance, while for 71 cm distance with 1.42% error, 72-100 cm distance with 1.12% error, and 100-200 cm distance with 1.23% error. Therefore, the distance measurement with HCR-04 can provide better results than the conventional distance measurement instruments.

This research discusses the challenges of developing metal detection sensors used as metal detectors underwater and as technology advances, new technologies have emerged, including the pulse-induction (PI) method. In simple terms, the PI method is based on the principle of electromagnetic echo, in which the loop consists of several coils of wire connected to the switch and connecting to the battery. In this way, the high electric current of the battery generates a magnetic field that induces current in metal objects. This current induction is converted into a display signal or some kind of indicator that identifies the presence of an object with a metal material [9]. To detect a metal, waves with an intermediate medium are able to propagate. Sound is vibration that can be transmitted by water, or other materials as a medium (intermediate). The speed of sound depends on the transmission by the medium. [12] Supporting equipment commonly used in surveying, excavation, and lifting of ships and BMKT includes GPS, ROV, magnetometers, air conditioning, acoustic systems, underwater cameras, and suction devices [13].

The purposes of the research are to design and develop a prototype of the remotely operated underwater vehicle with a Penta Tubular design which is completed by the control system of motion, ultrasonic-based distance sensor, and inductive proximity sensor. The research is directed to develop distance measurement tools that can be used wirelessly. The measurement range of the inductive distance sensor is between starting from 0.1 cm to 5 cm. This research will develop such sensors by using new technologies for microsystem integration. The size of the integrated sensor chip is 1.5 x 2 mm, with a square coil of 1 x1 mm. This miniature flat coil has an inductance of 75 nHc [10].

2. The Design Stages of Remotely Operated Underwater Vehicle (ROUV)

Based on the purpose of research and literature review, the previous research started with the design of the physical structure of the remotely operated underwater vehicle which is defined as Penta Tubular, and followed with setting up all electronic components to control maneuvering, distance sensor, and inductive proximity sensor. Some considerations were also taken to set up the ROUV weight point and resistance, and finally, testing and inspection of the ROUV operation were carried out.

2.1. Design of ROUV

ROUV is designed as a Tubular Penta model as shown in Figure 1, which is a form of ROUV consisting of 5 (five) tubes that are interconnected and can be operated with lower resistance, more dynamic motion processing, more space to accommodate the work equipment and space for sufficient ballast systems. This Penta Tubular form has 5 pipe tubes, including one pipe tube as the main hull (pressure hull) with 4 ballast hulls below, and the right and left side of the main hull. The ROUV design with the Penta Tubular model allows ballast control as a means of buoyancy/ sinking ROUV and more optimal motion processing.

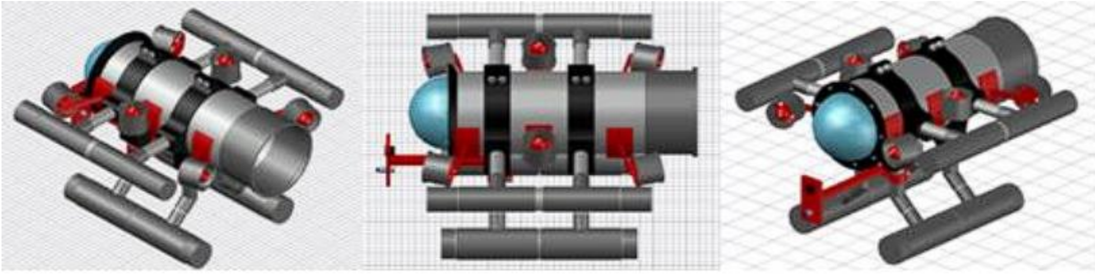


Figure 1. 3D Model of ROUV Penta Tubular

The main hull of ROUV uses a 6-inch (16.5 cm) pipe with a length of 46 cm. The 6-inch pipe was chosen because it has a diameter that is considered sufficient to accommodate the width of the components used in ROUV. The Ballast tubes under the ROUV probe use PVC pipes measuring 2 inches (60 mm) with a length of 36.5 cm. The 2-inch PVC pipe for the lower ballast tube is used to accommodate the needs of three ballasts with a diameter of 2.5 cm, a length of 22.2 cm with a total weight requirement of 2.55 kg each. The right and left side ballast tubes use PVC pipes with a diameter of 11/2 inches (48 mm) with a length of 42.5 cm. Each tube will hold one ballast with a diameter of 2.5 cm with a length of 22.2 cm with the total weight requirement on each tube of 0.85 kg (see Table 1).

Table 1. Dimensions of Penta Tubular Type ROUV

Dimension	Size	Unit
Length Overall (LoA)	59	cm
Breadth (B)	53.6	cm
Height (H)	40.74	cm

ROUV is designed to operate at a maximum depth of 1 meter from the surface of the water. When diving there will be hydrostatic pressure that will suppress ROUV, the deeper the diving vehicle, the greater the hydrostatic pressure received. Here is the calculation of the hydrostatic pressure received by ROUV at an operating depth of 1 meter:

$$P_h = P_{atm} + \rho G h \quad (1)$$

Where, P_h: Hydrostatic pressure (N/m^2)
P_{atm}: Atmospheric pressure (Pa)
G: Acceleration of gravity (m/s^2)
ρ: Density of water (kg/m^3)
h: Depth (m)

PVC pipe used in ROUV is an AW class PVC pipe which has ability to withstand pressures up to 8 bar (800,000 N/m^2) based on SNI data. Under maximum operating conditions, ROUV gets a hydrostatic force of your axis 1.11125 Bar (111.125 N/m^2) so the use of PVC material is very safe because the hydrostatic force produced is smaller than the ability of PVC material to withstand the compressive pressure.

ROUV is equipped with 6 motors consisting of 2 motors as forward and turn drives, 2 motors as reverse and turn drives, and 2 motors as up/ down drives (dives). 6 motors are connected to 6 ESC (Electronic Speed Controller) with a power drive of 3 batteries with a capacity of 2200mAh. The ROUV is equipped with a camera for navigation, an ultrasonic proximity sensor JSN-SR04T, and an inductive proximity sensor type LJ12A3. The control system used in ROUV is a keyboard that uses six keywords to control maneuvers. The control method used is the open loop category so that the ride does not provide feedback from its operation. The maneuvers that can be done are forward, backward, turn right, turn left, and go up / down (dive). The motor parts used in ROUV are as follows (see Figure 2):

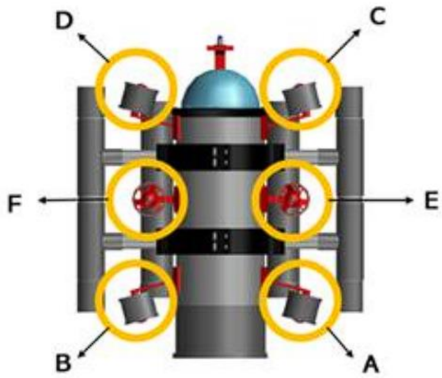


Figure 2. The Division Motor at ROUV Penta Tubular

2.2. Design and Configuration of Electronic Components

The ROUV drive system is designed using six brushless pusher motors with two motors placed in the rear, two motors placed aside, and two motors installed in front. The motor is directly connected to the electronic speed controller (ESC). Where ESC has a function as a motor speed regulator and adjusts the amount of current required by the motor. The ESC used has a maximum capacity of 30A. After being connected to the motor, ESC is then connected to the battery as a power supply, the battery used is a type of Lippo Battery with a capacity of 2200 mAh. The sensor used on the vehicle consists of 2 sensors, namely the JSN-SR04T type ultrasonic proximity sensor, and the LJ12A3 type inductive proximity sensor as a metal detector sensor. The design of the ROUV electrified component can be seen in Figure 3.

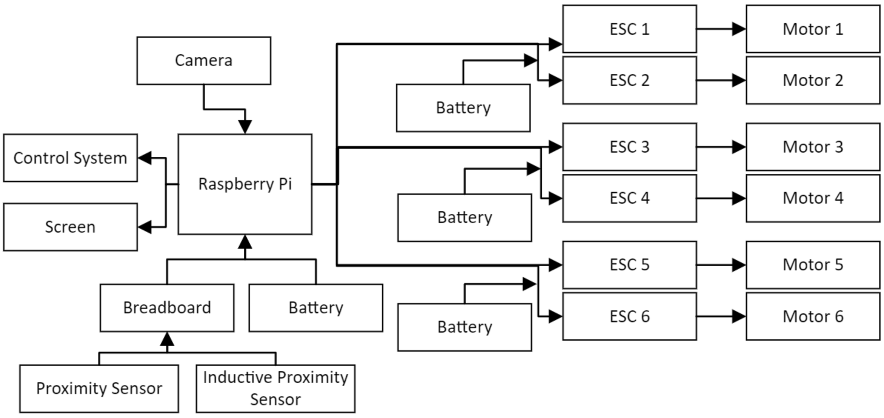


Figure 3. Electronic ROUV Component System Diagram

In ROUV, micro-controller is used as a processor for operating sensing proximity sensors (JSN-SR04T), inductive proximity sensor LJ12A3, camera, while the micro-controller used is Raspberry-Pi. On ROUV, the division of raspberry-pi GPIO pins for motors and sensors is as follows:

Table 2. Division of GPIO Pins for Motors

ESC	Board	
	GPIO	GND
ESC 1 (Motor A)	11	9
ESC 2 (Motor B)	13	14
ESC 3 (Motor C)	15	20
ESC 4 (Engine D)	16	25
ESC 5 (Engine E)	18	30
ESC 6 (Motor F)	22	34

Table 3. GPIO Pin Sharing for Sensors

Type	Board Number
Ultrasonic	
(R_x) Trig (GPIO)	10
(T_x) Echo (GPIO)	8
GND	6
Proximity	
GPIO	29
GND	39

2.3. Calculation of Weight Point

The weight of ROUV was calculated on 2 (two) conditions such as 1) ROUV without ballast, and 2) ROUV with full ballast. In conditions without ballast, ROUV weight is 9.3 Kg, while in conditions with full ballast, ROUV weight is 16.1 Kg. For conditions with full ballast, 8 permanent ballasts were made of cylindrical iron with a diameter of 2.5 cm and a length of 22.2 cm, with a weight of 0.85 Kg for each permanent ballast.

The ROUV weight points are calculated using the solid-work method as a reference for the location of the weight points on the ROUV. The calculation of the weight point in the solid-work method is carried out by modeling the ROUV into a three-dimensional (3D) model according to its dimensions, with the weight duck of the ROV calculated from the middle point at the front. After modeling, here are the results of the analysis obtained from the solid-work method, see Table 4.

Table 4. The Analysis of ROUV Weight Point

Parameter		Value	Unit
Mass		14.505	Medical history
Volume		0.004327	m3
Surface Area		2.232	m2
Weight	X	0	mm
Point	And	207.19	mm
	With	191.41	mm

2.4. Calculation of Resistance

The calculation of resistance in ROUV is calculated numerically referring to Fluid Mechanics Fundamentals and Applications. In simple terms, the ROUV vehicle is divided into 5 main tubes with 3 different dimensions with 4 connecting pipes of the same size. Therefore, the ROUV resistance analysis can be calculated through the formula:

$$F_d = \frac{1}{2}\left(\rho \times C_d \times A \times V^2\right) \quad (2)$$

Before calculating the resistance, the frontal area and drag coefficient of each hull need to be known. The drag coefficient of each section is calculated using the interpolation of the drag coefficient of each shape for the dimension of the model. As for the results of the calculation of resistance for ROUV with a design speed of 1 m/s, see Table 5 as follows:

Table 5. The Calculation of ROUV Resistance

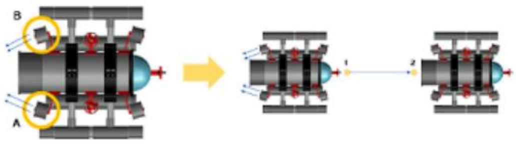
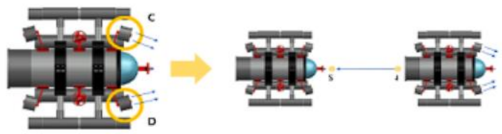
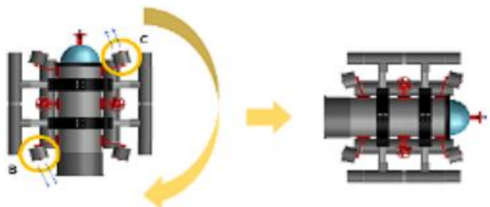
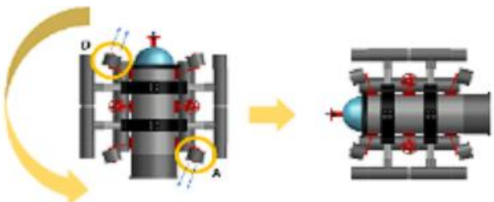
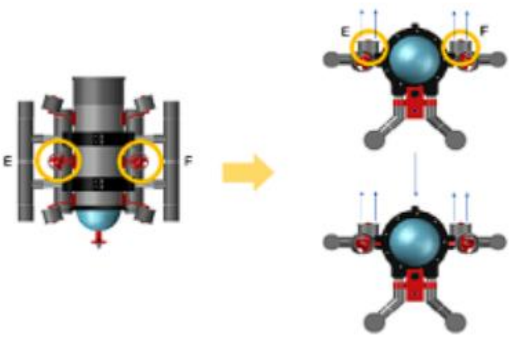
Part	A (m^2)	L/D	C_d	F_d (N)
Pressure Hull	0.02139	3.21	0.7	7.487
Lower Ballast	0.00283	6.08	0.952	2.693
Side Ballast	0.00181	8.854	1.0214	1.849
Side Ballast Connector	0.000531	2.5	0.617	0.328
Lower Ballast Connector (45°)	0.000531	2.46	0.615	0.327
Lower Ballast Connector	0.000531	2.692	0.623	0.331
			Total	12.356

3. Results and Discussion

3.1. ROUV Maneuver Testing

Maneuver Testing on ROUV is divided into 5 test groups consisting of forward motion, reverse motion, right-turn motion, left-turn motion, and dive motion. The maneuver on the ROUV is controlled by a controller in the form of a keyboard connected via a wired network to the Raspberry Pi. In the ROUV maneuver control, several keywords are used to control ROUV as shown in Table 6, as follows:

Table 6. The Calculation of ROUV Resistance

Keyword	Order	Result
In	Forward (Motors A and B)	
S	Backward (Motor D and C)	
A	Turn Left (Motor A and D)	
D	Turn Right (Motor B and C)	
With	Dive (Motor E and F)	

3.2. Ultrasonic Proximity Sensor Testing

The test of the proximity sensor on the air medium is carried out by placing the sensor with the detection object at the specified distance variation and before the test is carried out, calibration is carried out on the device so that the resulting detection distance is accurate. The distance measurement test in Figure 4 and the data results of the JSN-SR04T-type ultrasonic distance sensor on the air medium is as follows:

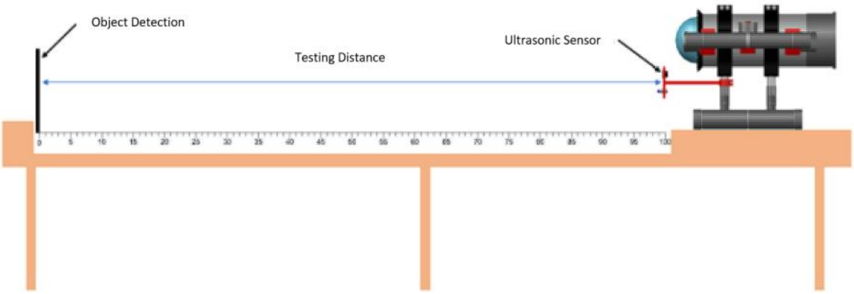


Figure 4. Ultrasonic Distance Test in Air Medium

Table 7. The Calculation of ROUV Resistance

Distance Variations	Average	Error (%)
Distance 20 cm	20.123	0.656 %
Distance 40 cm	40.229	0.569%
Distance 60 cm	60.036	0.06%
Distance 80 cm	80.102	0.127%
Distance 100 cm	100.71	0.705%

From the test result data in Table 7, it was found that the percentage of error from the JSN-SR04T type ultrasonic distance sensor test on the air medium was still below 1%, with the smallest error percent 0.06% and the highest error percent 0.705%.

The program used for testing ultrasonic distance sensors underwater needs to be distinguished from the program for testing the air medium. This is done because of the difference in the speed of propagation of sound waves in different mediums, so it is necessary to recalibrate the device so that the detection distance produced is accurate. In water medium, the propagation speed of sound waves ranges from 1500 m / s to 1520 m / s, when compared to the speed of propagation of sound waves in air medium which ranges from 330 m / s to 343 m / s, then the speed of propagation of sound waves in water medium as shown in Figure 5, is 4.487 times faster. The test data results of the JSN-SR04T-type ultrasonic distance sensor on the water medium can be seen in Table 8.

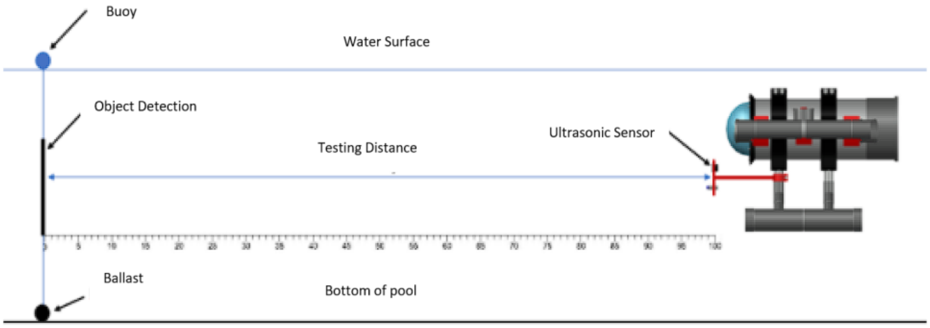


Figure 5. Ultrasonic Distance Test in Water Medium

Table 8. Water Medium Distance Measurement Results

Distance Variations	Average	Error (%)
Distance 20 cm	89.946	Minimum
Distance 40 cm	89.958	Detection Limit
Distance 60 cm	89.951	
Distance 80 cm	89.941	
Distance 100 cm	99.516	0.49%

From the test result data in Table 8, it was found that the JSN-SR04T-type ultrasonic distance sensor can only read the distance underwater at a distance variation of 100cm with an error percentage of 0.49%. At a distance variation of 20 cm to 80 cm, the average overall data read by the sensor is 89.949 cm. This data reading error occurs because of the minimum limit of the sensor to be able to read the distance of the object. In the air medium, the minimum reading distance of the object is 20 cm, with the propagation speed of the sound waves in the air medium is 336.5 m/s, the time it takes for the sound wave to travel the distance from the start of the transmitter to return to the receiver is 0.001189 seconds with a total sound wave mileage of 40 cm.

In water medium, the average propagation speed of sound waves is 1510 m/s, when compared to the speed of sound propagation in air medium, the speed of sound propagation in water medium has a value of 4.487 times faster.

The limit of the ability of the JSN-SR04T type sensor to emit sound waves from the transmitter until it is recaptured through the receiver is 0.001189 seconds, then the minimum distance that can be read by the JSN-SR04T type sensor on the water medium can be searched through the following calculations:

$$T_{max}\text{: } 0.001189 \text{ s} \quad (3)$$

V: 1510 m/s

$$v = \frac{s}{t}$$

$$s = 1510 \times 0.001189$$

$$s = 1.795\ m$$

Thus, the minimum test distance that can be read by the sensor is 89.75 cm, therefore the detection object located less than 89.75 cm is unreadable and only displays the minimum distance data that can be read by the sensor.

3.3. Inductive Proximity Sensor Testing

The testing of the LJ12A3 type proximity sensor on the air medium was carried out by placing a sensor with a detection object at a distance between 0-5 mm. The proximity sensor test in the air medium and results of the LJ12A3 type proximity sensor test data on the air medium are as follows:

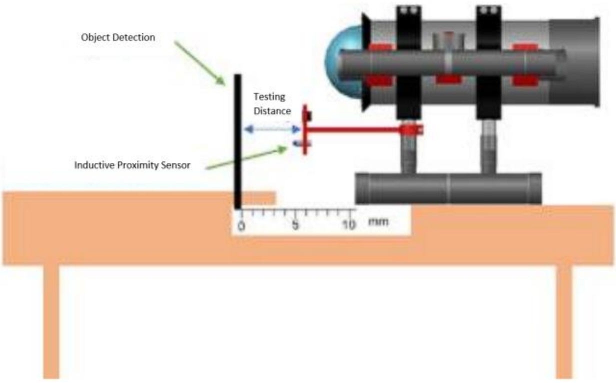


Figure 6. Proximity Sensor Test in Air Medium

Table 9. Proximity Sensor Test Results on Air Medium

Material	Accuracy
Steel Plates	100%
Aluminum Plates	100%
PVC Plates	100%

From the test result data in Table 9, it was found that the percentage of test success of the LJ12A3 type proximity sensor on the air medium for steel plate material, aluminum plates, and PVC plates was 100%. The test of the LJ12A3 type proximity sensor on the water medium was carried out by running the ROUV until the proximity sensor at the front end of the ROUV approached or attached to the detection object. The proximity sensor test in water medium and results of the LJ12A3 proximity sensor test data on the water medium are as follows:

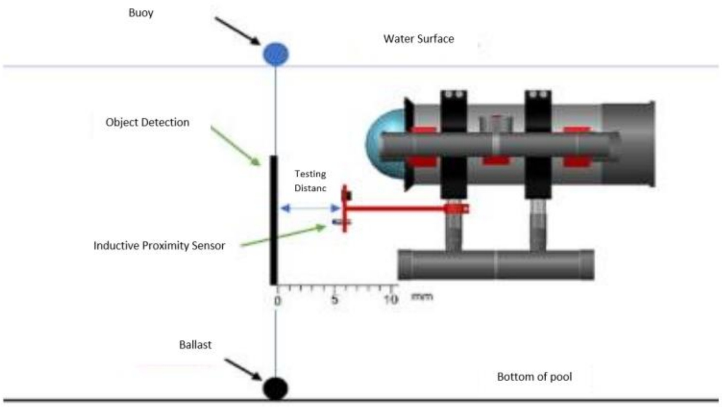


Figure 7. Proximity Sensor Test in Water Medium

Table 10. Proximity Sensor Test Results on Water Medium

Material	Accuracy
Steel Plates	100%
Aluminum Plates	100%
PVC Plates	100%

From the test result data in Table 10, it was found that in metal materials, all samples received "detected" test results which indicates that the accuracy of the metal detector sensor to detect metal materials underwater is 100%. Meanwhile, in non-metallic materials, namely PVC plates, from 10 tests, 10 data were obtained, indicating that metal detector sensors cannot be used to detect objects other than objects with metal materials.

4. Conclusion

The results of this study resulted in the following conclusions:

- The ROUV is designed with the single main tube as a pressure hull with 4 ballast tubes, located under the main tube at the left and right wing of the main tube. The designed ROUV has 6 electric motors, 6 electronic speed controllers, 3 unit batteries, a navigation camera, an ultrasonic-based distance sensor, and an inductive proximity sensor.
- For maneuvering, the ROUV uses open loop control for forward, backward, turn left, turn right, and dive, and can be demonstrated smoothly.
- For air medium, the result of the trial test of the ultrasonic-based distance sensor, has a deviation between 0.666% to 0.705%, and 100% detection for steel material with inductive proximity sensor method
- For water medium, the result of the trial test of the ultrasonic-based distance sensor has a deviation of 0.49%, and 100% detection for steel material with inductive proximity sensor method
- For both air and water mediums, the result of the trial test of the ultrasonic-based distance sensor and inductive proximity sensor method cannot detect non-steel materials

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