Development of a Low-Cost Remotely Operated Vehicle for Ocean Exploration

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***Abstract*—Remotely Operated Vehicles (ROVs) are expensive and complicated systems for ocean exploration. ROVs are playing more and more important roles in the exploration of the ocean and fishery industry. If we could build a low-cost ROV so that people could afford it, then more and more people will have the opportunities to explore the ocean. In 2014，the Science and Technology on Underwater Vehicle Laboratory at Harbin Engineering University started a low-cost ROV project. The goal of this project is to develop a small inspection-class ROV that carries a video camera for underwater inspection. The ROV's total weight in the air is less than 10kg. The depth rating of the ROV is 150m and the maximum speed is 4 knots. The total cost is controlled under $4000. This paper presents the details of this ROV design and test results.**

Keywords—ROVs; Underwater thrusters; Pressure housing

I. INTRODUCTION

A. What is an ROV

A Remotely Operated Vehicles (ROV) is an unmanned vehicle controlled by a human from a remote location to carry various professional underwater equipments to explore the underwater environments. ROVs are used in a variety of sectors of our economy, including the following: oil and gas exploration and extraction; telecommunications, such as the laying of fiber optic cable; science and research; underwater archeology; search and recovery; safe navigation; defense and homeland security; and a variety of different types of inspections, from ships, bridges to nuclear power plants [1]. The ROV industry is dominated by large, work-class electro-hydraulic ROV systems, such as the Seaeye Sabertooth ROV [2] and Mohawk ROV [3], which play an important role in ocean exploration. However, these ROVs are so expensive and so heavy (over 100Kg) for personal users. So people build some small ROVs to do the ocean exploration work. Among these ROVs, the inspection-class ROVs that can carry a camera to obtain the real-time underwater video images are popular allover the world. Those vehicles can be used to monitor events on the seafloor or in the water and streamed some amazing video to the ground station in real time while the operator remains clear of harm's way. They also can collect data such as temperature, depth, heading, pitch, roll, motor speed, and water leakage with sensors to feedback the state of the ROV and its surroundings. Most importantly, they are easy to build and not so expensive. An ROV may have lots of sensors, but the most important sensor of the inspection-class ROV is the camera which acts as the eye to observe the underwater environment.

B. Project Background

In 2014, a group of graduate students from Harbin Engineering University started a project to build a low-cost ROV for underwater inspection at depths up to 150 meters. This ROV can be used as a platform for future engineering research or as an educational tool to educate students. The initial design of this ROV (version 1.0) is shown in Fig.1. When designing this ROV, we set four major design goals: low cost, simple structure, high maneuverability, and the ability to used in future research project. Thus, we tried to build the ROV as small as possible. However, our ROV version 1.0 was so big and heavy and it was hard to lift. Therefore, we design another ROV version 2.0.

C. Current Status

The second ROV was successfully completed in June 2015 by a team of three students supervised by a professor. After several tests, the ROV meets all of the expectations and some of the specifications exceeded the team's expectation, e.g. maximum diving depth and speed.

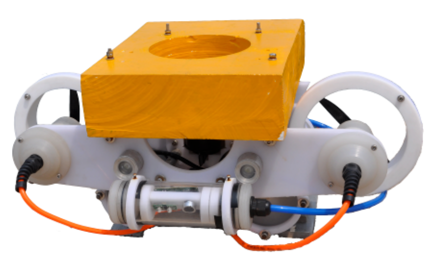

Fig. 1. ROV version 1.0

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II. STRUCTURE DESIGN

Some inspection-class ROVs are designed for fun such as the OPENROV[4] shown in Fig.2, which has a maxium depth rating of 75 meters. Even though this ROV is a low-cost and lightweight vehicle, there are some drawbacks: the structural design makes itself dangerous to move in harsh environment; its frame configuration gerenates great resistance when traveling underwater; its fragile acrylic housing and end caps cannot ensure to resist 75m water's pressure all the time; its space is limited to mount more sensors; its thrusters cannot provide enough forces for the ROV to run and dive faster; the energy of the ROV is limited.

Fig. 2. OPENROV

Another commercially available ROVs are VideoRay [5] ROVs shown in Fig.3, which perform excellently in the underwater research feild. This ROV almost overcomes all the drawbacks mentioned above. However, a lowend VideoRay ROV still costs more than $10,000, which is beyond most hobbyists' and educational groups' budgets.

Fig. 3. VideoRay ROV

There are many other types of inspection-class ROVs on the markets, such as Seabotix ROV [6], Outland ROV [7], Seawolf ROV [8], and Seamor 300F ROV [9] that we can refer to for our project. Generally, the design of these ROVs all consist of the control system housing fixed to rigid frames beneath a buoyancy materials (invariably yellow) and feature some kind of landing skid on the bottom. Thrusters are typically placed mid-plane in order to produce balanced motion, and separated by a distance to improve the maneuverability. The video camera is placed centrally on the front, with floodlights on both side (when present).

In our ROV design, we chose the polyethylene (PE) materials as the frame for the ROV system. The frame is cut from a 10mm thick PE plate by an engraving machine. We put the PE pieces together to hold the housing, thrusters, and LED floodlights in place. We use the veneer frame to mount electronics in the housing. For this ROV structure design, the budget, maneuverability, low-resistance are the main concerns. In the following section, two structure design prototyes will be discussed.

A. First Initial Concept ROV

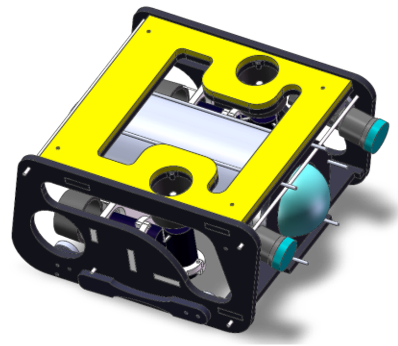

Fig. 4. First Initial Concept ROV

The main structure of the first initial concept ROV shown in Fig.4 consists of five plates, ten supporting rods, the housing mounting loops, and the top foam. The plates are made of PE plastic, chosen for its stiffness. Its density is very close to water. The plate design had to be strong and allow for enough water flow through so the ROV could maneuver easily. The supporting rods used to serve as a method to align the plates together and provide structural strength. The five plates are the top, port, starboard, front, and back plates.

The port and starboard plates hold the two vertical thrusters, two horizontal thrusters, and two LED floodlights. The wide space between the port plate and the starboard plate serves to give the horizontal thrusters plenty of distance from the center of gravity to allow for easy turning. The large circular holes on the plate cut out benefit on weight and permit the water flow through. These two plates are aligned together by the top plate, front plate, back plate, and four rods.

The front, back, top plates are designed to hold the housing and the strain relief of the tether. These plates are placed horizontally to reduce the contact area with the flow so that the ROV could have a lower the resistance when it travels in the water. The top foam is set on the top plate and four thrusters are mounted below the center of the height while the vertical thrusters must be placed at the middle of the longitudinal direction. By this way, we can keep the ROV balance in the water.

These plates are held together through the use of supporting rods. In total, ten rods are used, four for plates, the others for housing. The rods are mounted to the plates by using screw with washers to clamp the plates onto the end of the rods. The other six rods evenly compress the end caps of the housing.

Overall there are few issues with the arrangement of the plates, motors, floodlights. The first issue is the maneuverability. The issue is caused by the push from the lateral flow force. The larger lateral plates the ROV has, the more force it encounters. Aslo,the large top plate makes it difficult to dive fast. Besides, these large plates need more material and rise the weight and dimension of the ROV.

The next issue came from the manufacturing and assembly. All the components including housing, lights, thrusters, and the IMU are surrounded by the port, starboard, top, front, and the back plates, which leaves limited space to mount or replace these components.

B. The Second Initial Concept ROV

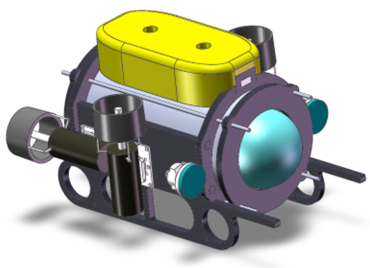

Fig. 5. Second Initial Concept ROV

The main structure of the second initial concept ROV shown in Fig.5 consists of port plate, starboard plate, front, back, and the top foam. The plates utilized the same material as the first initial concept ROV while they had smaller dimension.

The port and the starboard plates holds four thrusters and two LED floodlights connecting the front and back plate with the four supporting rods. The design of the front and back plates are designed to be as small as possible while still maintaining enough strength to hold the port, starboard, and the housing in place. The large holes at the bottom of the port and starboard plates serves to give the way to the lateral flow to pass through and decrease the weight of the ROV. Two PE sticks pointing to the front are designed to prevent the acrylic dome from crash.

The foam is placed right above the housing to supply buoyancy. The four thrusters are mounted outside of the port and starboard plates below the center of the height. By this way, we can make the buoyant center on top of the center of gravity, thereby keeping ROV balanced.

To sum up, this initial concept ROV is easier to manufacture than the first initial concept ROV, while it also has a maneuverability issue with the arrangement of the thrusters. The design issue had to do with the placement of the vertical thrusters at the middle of the longitudinal direction. Only in this way, the ROV can keep balance when it dives down or floats up. Consequently, the horizontal thrusters have to move backward, resulting in the center of the gravity retreating and increasing the radius of gyration.

C. The Final Design

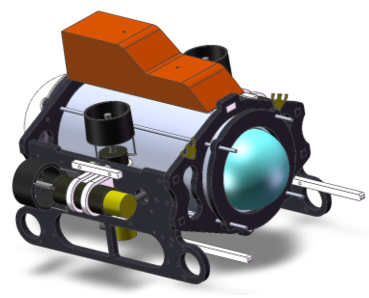

Fig. 6. Final Design

Based on the two initial concept designs of ROVs, the final design is shown in Fig.6. The design details will be discussed in the next two sections.

III. DESIGN CONSTRAINTS

The challenges that were encontered when designing this ROV were: Waterproofing, Depth Rating, Corrosion, Cost, Size, and Expandablity.

A. Waterproofing

The housing was required to provide a water free environment for the electronics. In this project we used O-rings as the watertight seals and the depth rating is 150m. Making the end caps for the pressure housing watertight took some machining on a lathe. For the rear end cap, we use aluminum, which acts as a heat dissipation for the four motor controllers mounted behind it. The front end cap includes a 4.5mm thick acrylic dome with 9.5mm wide border that allows the camera to tilt up and down without introducing optical distortion, shown in Fig.7.

Fig. 7. Dome

During the manufacturing of the ROV, there are some connecting work between wires, which need to be waterproof. To solve this issue, we made little box of veneer shown in Fig.8 to hold the wire connector and then filled in the remainder space with Epoxy Adhesive. In this way, the connector can stand up the high pressure and provide a mounting jacket for the wire at the same time.

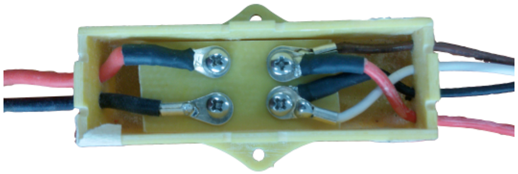

Fig. 8. Wire Conecting Box

B. Depth Rating[10]

As mentioned above, the ROV must be operated at depth upto to 150m. At this depth, the ROV should insist the changing pressure when diving. Assume that the density of the water is 1000kg/m^3, disregarding the changes associated with the temperature. Then, the relationship between pressure and depth can be approximated as shown in (3). The pressure we calculate herein is the value we use in the following pressure testing.

$$\rho=1000kg/m^3 \tag{1}$$

$$g=9.8m/s^2 \tag{2}$$

$$p=\rho gh=1.47Mpa \tag{3}$$

C. Corrosion

The ROV is designed for operation in a chlorinated pool, in fresh water or in salt-water environment. The rear end cap is made of aluminum which needs antioxidant retreatment. The rods made of stainless steel can be expediently replaced at a regular intervals. The other major materials are plastic so that we do not need to worry about the corrosion of the frame in the salt-water .

D. Cost

The main purpose of this ROV project is to build a low-cost ROV so that more people can afford it and use it to explore and research the underwater world. Therefore, we must always take the budget into consideration during the design process. A list of the components and materials we used in this project is included later in this document.

E. Size

When we built the ROV version 1.0, we realized that the larger the ROV is, the harder to move and launch the ROV. Besides, a larger ROV needs more materials and more powerful thrusters to push it. At the same time, the ROV should be designed to have enough room for the thrusters, lights, and electronics. So, the overall goal was to make the ROV as small as possible but flexible enough for the future modifications and research use.

F. Expandability

The intention of this ROV project was to design a platform to test the vision system and the motion control system and to carry different sensors to detect the feature of the underwater environment. To meet this goal, the ROV was designed to have spare room not only inside the housing but also on the frame. The additional room will allow for different electronics and sensors mounted inside the housing and thrusters placed on the frame. We also have a spare subsea through-hole connector on the end cap for future modifications.

IV. COMPONENTS

A. Housing

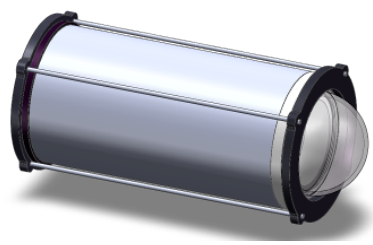

Fig. 9. Housing

Because the commercially available housings were well beyond our budget, a 300mm long, 160mm in diameter Unplasticized Polyvinyl Chloride (UPVC) tube was selected as our waterproof housing instead of using expensive metal housing. Compared to the metal materials, the UPVC has some good properties, such as low cost, noncorrosive, high strength, low density, smooth surface, and perfect mechanical processability.

We bought an acrylic dome as the front observation window for the camera instead of expensive custom-made dome. The end cap on the tail of the waterproof housing is made of #6061 Aluminum. The reason for using Aluminum instead of plastic material is because Aluminum is a much better material in transmitting heat generated from electronics inside the housing.

Inside of the housing are four motor controllers, an ODROID-XU3 single board computer, an Arduino Mega2560 motion control board, a 720P webcam, a servo, a temperature sensor, and two transformers.

When we built the ROV version 1.0 last year, we used so much buoyant material that the ROV was too heavy to move and launch. So we decided to enlarge the housing which was able to supply some buoyancy for the ROV replacing some buoyant material, along with more space in the housing for future modification.

B. Thrusters

Fig. 10. Thruster of the ROV Verson 1.0

Initially, we used bilge pump motors as the thrusters shown in Fig.10 on the ROV version 1.0, because of the low cost. However, these motors did not perform well in the sea trail due to low power and low efficiency. We wanted our next version of ROV to be able to go deeper and faster. So we bought four 400HFS-L thrusters shown in Fig.11 from CrustCrawler Inc[11] with a total cost of $2396.

Fig. 11. 400HFS-L Thruster

However, the cables came with the thrusters were too short to be connected to the waterproof housing. Thus we need to connect another piece of cable with through-hole connecter and then seal the connector with 3M Scotchcast 2130 Flame Retardant Compound. This would cost a few hundreds of dollars. In order to reduce the cost, we used Loctite E-120HP Epoxy and self-made jacket shown in Fig.12 which is only $2 per piece.

Fig. 12. Self-made Jacket

C. LED Floodlights

Fig. 13. LED Floodlight

Originally, we made four waterproof lights (the left one shown in Fig.13). However, it was too big to be mounted on the ROV. Fortunately, we found replacement: the eagle-eye LED light, the right one shown in Fig.13. We covered gap around the dome of the light with a generous amount of Loctite's Epoxy Adhesive—an important trick to keep LED floodlights waterproof. To illuminate farther objects underwater, we also added two underwater flashlights on both side of the front plate. So a total of six LED lights are mounted on the ROV.

D. Foam Top

The orange buoyant brick shown in Fig.6 is screwed on the top of the housing to provide enough buoyancy and stabilize the ROV. It is made of glass microballoons and Epoxy with half density of the water. To identify the vehicle easily in the water, we spray orange paint on the foam top.

E. Tether

The tether connecting the ROV with the ground station is split into two parts: a power cable and an ultra-thin data cable. We tie both cables together with foam ball attached at intervals; a neutrally buoyant tether would have been better, but pricey. The data cable contains one twisted pair of wires and two Power Line Communication (PLC) boards at both ends which will allow the data cable carries control signal from the ground station down to the ROV and the ROV data signal up to the surface at the same time. The PLC boards from Tenda Homeplug Adapter make it possible to operate ROV with a much longer data cable if desired.

F. Through-hole Connectors

One particular challenge is to connect the electronics and microcontroller inside the housing with the motors and the cable outside through the rear end cap. We bought six through-hole connectors from SubConn Inc. to prevent the housing from leaking and make our ROV to be able to dive deeper, even though they are a little bit expensive.

G. Electrical System

As for the control system of the ROV, we used an ODROID-XU3 single board computer as server to connect with the control station on the surface by PLC technology. By using this design, we could use a regular power cable to transmit signal between ROV and ground station. The ground station could be any smart phones or tablets connected to a wireless router. The wireless router is connected to the ROV through a pair of twisted wires via PLC adapter. Therefore, there is no need to buy the costly fiber optic cables and expensive display monitors for the ground station. In order to get high resolution pictures, we bought a 1080P webcam which is only $59. This camera works very well and is much cheaper than the professional underwater cameras. The webcam can transmit real-time video directly to the ground station. The control signal is sent to the microcontroller (Arduino Mega2560) which will command the four thrusters and six lights and collect the data from the sensors for the ground station at the same time. Fig.14 shows the electronics system architecture.

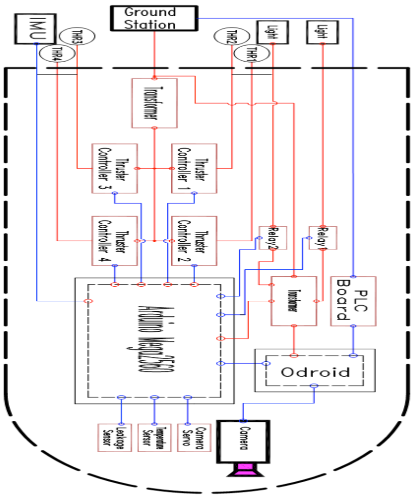

Fig. 14. Electronics System

V. TEST RESULTS

The foremost expectation of the ROV is to be able to operate at depth up to 150m. This includes keeping the housing and connectors waterproof and obtaining good quality of realtime videos. Lastly, the total cost of the whole ROV system must be under $4000. To confirm that the ROV meets this expectation, we need to do two kinds of tests.

A. *Pressure Testing*

We tested our waterproof housing, thrusters, and lights design in the test chamber, which is capable of simulating pressures at 2,000-meter depth. The housing, thrusters, and lights survived at 1.47Mpa with no damage.

B. *In Water Testing*

At this point, the ROV's motion-control capability was tested in a 50m x 30m x 10m test pool. All the systems worked pretty well. The ROV went up and down easily when we operated the vertical thrusters and it turned out to be very responsive in the horizontal plane, too. Fig.15 shows the image captured by ROV which is clear enough to locate the target in the water.

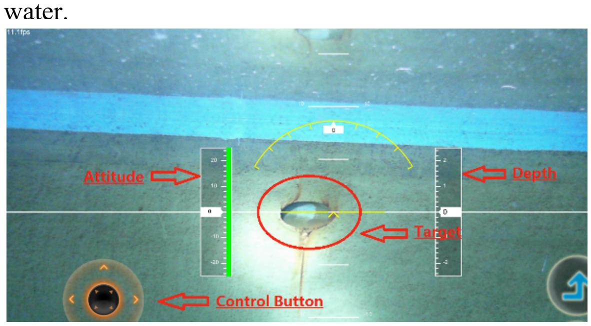

Fig. 15. Groud Station GUI

VI. BUDGET

Every component was selected with consideration of function and cost. Especially, the materials of the frame, housing, and the wire connector is relatively cheap and valid. This kept the main components costs to a minimum because custom subsea housing, connectors or carbon fiber frame were not required. Most of components were bought on Taobao. Machine work was completed in house by ourselves if possible.

Table I presents a list of all components purchased to produce the ROV.

TABLE I. ITEMIZED ROV BUDGET

Item	Vendor	Qty	Total cost($)
Eagle Light	Taobao	4	2.16
Flash Light	Taobao	2	6.6
Thruster	CrustCrawler Inc.	4	2396
Through-hole Connector	Subconn	6	210
Odroid	Sumsung	1	200
O-ring	Taobao	3	0.9
UPVC Tube	Taobao	1	6.3
Epoxy Glue	3M	5	41.5
Acrylic Dome	Taobao	1	30
Aviaton Plug	Taobao	6	1.98
Ardunio Mega2560	Taobao	1	10
Transformer	Taobao	2	20
Webcam	Microsoft	1	59
Screw	Taobao	20	0.6
Veneer Plate	Taobao	1	4.5
Rod	Taobao	5	4
Cable	Taobao	2	42
Orange Paint	Taobao	1	1
Teflon Tube	Taobao	1	20
Thruster Controller	Phoenix 60A	4	640
Servo	Emax	1	3
Relay	Taobao	2	1
PE Plate	Taobao	1	30
PLC Board	Tenda	2	20
IMU	Taobao	1	10
PP Plate	Taobao	1	1
6061 Aluminum Bar	Taobao	1	10
Total Cost			**3771.54**

VII. CONCLUSION

For this project, since the cost is a major factor in the design process, the major components of the ROV are self-made and the rest are modified from off the shelf parts. The total cost of the ROV version 2.0 shown in Fig.16 was controlled to be under $3500 and the ROV still met our design specifications. This low-cost ROV design will make the ocean exploration task more affordable.

Fig. 16. ROV Version 2.0

The main specification as follows:

1) Physical Specification

a) Weight:10Kg

b) Dimensions: 50 ×40×40cm(l×w×h)

c) Operating Voltage Range: 40-50V

2) Performance Specification

a) Maximum Depth:150m

b) Maximum Forward Speed: 4Knots

c) Camera Tilt:+/-60 deg from center

ACKNOWLEDGMENT

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