Research, design and control of a remotely operated underwater vehicle

DUY ANH NGUYEN [1], QUANG HUNG CAO [1], PHUNG HUNG NGUYEN [2]
[1]Dept. of Mechatronics, the Faculty of Mechanical Engineering, HCM City University of Technology, Vietnam
[2]Faculty of Navigation, HCM City University of Transport, Viet Nam
Email: duyanhnguyen@hcmut.edu.vn

Abstract: This paper will present the initial results of the design, construction and control a mini remotely operated underwater vehicle (ROV) for marine research, including hardware and software control. This ROV is equipped with gyroscope, accelerometer, compass, pressure sensors for performing underwater movement. It has six motors, two for vertical and four for horizontal movement. Control commands and feedback sensor are transferred using RS485 bus. PID controllers would control heading angle and depth of the system. Visual studio C# 2013 is used to design the controller interface.

Keywords: *ROV, thruster, PID Controller, Control Algorithm*

Introduction:

Unmanned underwater vehicles (UUV) are submarine robot which classified in two main categories: remote operated vehicle (ROV) and autonomous underwater vehicle (AUV). A ROV difference from AUV in a way that ROV always take command from its operator and takes no action autonomously. This paper focuses research about ROV which connected to the surface through a cable or umbilical line and is fully controlled by human directly using remote control. It can perform variety underwater tasks including assisting offshore exploration, repair and maintenance, studying marine life and collecting deep water samples,... In most cases, ROV can operate more accurate, reliable and productive than human.

The purpose of this work is to design and develop a mini ROV with low cost, suitable mechanical structure and self-stabilized due to serving education. A control algorithm will be built for flexible movement in various directions such as forward and backward motion, turning left, turning right, diving and floating while it still maintains the stability and move with constant velocity. Feedback signals from compass and pressure sensor are combined with PID controller to control heading angle with error $\pm 2^0$ and depth with error ±0.05m. Parameters of PID controller are determined by trial and error method. The research in this paper is divided into three parts, including mechanical design, electrical design, control algorithm and software.

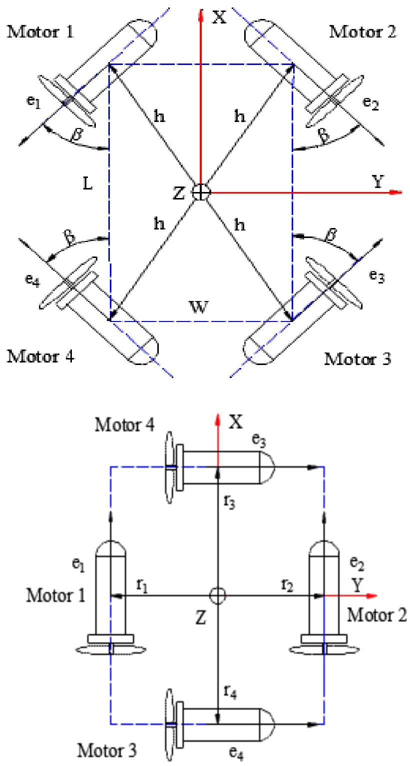
Materials and Methods:

Mechanical Design

Thruster and optimal thrust allocation.

Six thrusters are used in the ROV. Each thruster is a servo DC motor sealed in the cylindrical hull connecting to the propeller. A mechanical seal is used to waterproof DC motor. The positions of the thrusters depend on the task of the ROV. After considering between having maximum manoeuvrability and power consumption, the suitable design includes two vertical and four horizontal thrusters. This arrangement of thruster allows control of surge, sway, heave, pitch and yaw motions.

Two thruster in the vertical direction provide enough load drag and improve the pitch stability for vehicle. The research is focused on the thrust allocation in horizontal plane. Usually, an open frame underwater vehicle has four horizontal thrusters, denoted Motor i, i=1, 2, 3, 4. There are two common configurations of the horizontal thrusters, X-shaped and Cross-shaped configurations (Figure 1). Their position and orientation are illustrated in table 1 and table 2.



(a) X-shaped configuration
(b) Cross-shaped configuration
Figure 1: Two configurations of the horizontal thrusters.

Therefore, the vectors of forces and moments, exerted by Motor, can be expressed as:

$$\vec{\tau}_i^{\text{Motor}} = \begin{bmatrix} {}^{i}\vec{F} \\ {}^{i}\vec{M} \end{bmatrix} \begin{bmatrix} {}^{i}F\vec{e}_i \\ {}^{i}F\left(\vec{r}_i \times \vec{e}_i\right) \end{bmatrix}$$

$$= \begin{bmatrix} e_{ix} & e_{iy} & \left(\vec{r}_i \times \vec{e}_i\right)_x & \left(\vec{r}_i \times \vec{e}_i\right)_y \end{bmatrix}^T {}^{i}F$$

Table 1: The position for the thruster configurations

	Motor 1	Motor 2	Motor 3	Motor 4
X-shaped Configuration	$\begin{bmatrix} \frac{L}{2} \\ -\frac{W}{2} \end{bmatrix}$	$\begin{bmatrix} \frac{L}{2} \\ \frac{W}{2} \end{bmatrix}$	$\begin{bmatrix} -\frac{L}{2} \\ \frac{W}{2} \end{bmatrix}$	$\begin{bmatrix} -\frac{L}{2} \\ -\frac{W}{2} \end{bmatrix}$
Cross-shaped Configuration	$\begin{bmatrix} 0 \\ -r_1 \end{bmatrix}$	$\begin{bmatrix} 0 \\ r_2 \end{bmatrix}$	$\begin{bmatrix} r_3 \\ 0 \end{bmatrix}$	$\begin{bmatrix} -r_4 \\ 0 \end{bmatrix}$

Table 2: The orientation for the thruster configurations

	e_1	e_2	e_3	e_4
X-shaped Configuration	$\begin{bmatrix} -\cos\beta \\ -\sin\beta \end{bmatrix}$	$\begin{bmatrix} -\cos\beta \\ \sin\beta \end{bmatrix}$	$\begin{bmatrix} \cos\beta \\ \sin\beta \end{bmatrix}$	$\begin{bmatrix} \cos\beta \\ -\sin\beta \end{bmatrix}$
Cross-shaped Configuration	$\begin{bmatrix} 1 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 1 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 1 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 1 \end{bmatrix}$

Where ${}^{i}\vec{F}$ is the force exerted by thruster i on the ROV, ${}^{i}\vec{M} = {}^{i}\vec{F} \times \left(\vec{r}_i \times \vec{e}_i\right)$ is the moment deduced from ${}^{i}\vec{F}$. The direction of ${}^{i}\vec{F}$ is decided by $\vec{e}_i = [e_{ix} \quad e_{iy}]$. We obtain:

$$\vec{\tau}^{\text{Motor}} = \sum_{i=1}^{4} \vec{\tau}_i^{\text{Motor}} = \sum_{i=1}^{4} \begin{bmatrix} {}^{i}\vec{F} \\ {}^{i}\vec{M} \end{bmatrix}$$

$$= \begin{bmatrix} e_{1x} & e_{2x} & e_{3x} & e_{4x} \\ e_{1y} & e_{2y} & e_{3y} & e_{4y} \\ \left(\vec{r}_1 \times \vec{e}_1\right)_x & \left(\vec{r}_2 \times \vec{e}_2\right)_x & \left(\vec{r}_3 \times \vec{e}_3\right)_x & \left(\vec{r}_4 \times \vec{e}_4\right)_x \\ \left(\vec{r}_1 \times \vec{e}_1\right)_y & \left(\vec{r}_2 \times \vec{e}_2\right)_y & \left(\vec{r}_3 \times \vec{e}_3\right)_y & \left(\vec{r}_4 \times \vec{e}_4\right)_y \end{bmatrix} \times \begin{bmatrix} {}^{1}\vec{F} \\ {}^{2}\vec{F} \\ {}^{3}\vec{F} \\ {}^{4}\vec{F} \end{bmatrix}$$

$$\vec{\tau}^{\text{Motor}} = \vec{R} \times \vec{F}$$

Where

$\vec{R} \in R^{4\times4}$ is the thruster's configuration matrix.

In order that ROV moves flexibly in various directions and force and rotation moment along directions are equal, X-shaped configuration and $\beta = 45^0$ are chosen.

Frame

Designing the frame is vital for the ROV, as providing the structure for the hull form and the components. The frame has been designed considering the following criteria:

- Material strength and availability.
- Ease of production and maintenance.
- Light weight and ease of assembly.
- Centre of gravity of the frame.
- It would be possible to add extra module, for example the module for camera.

Each parameter was evaluated. The ROV was constructed by low cost material like commercial grade polyvinyl chloride (PVC) pipes. This frame proved successful in the test and will be extended to provide supports for multiple pressure vessel and other components. The overall dimension of the vehicle is 700mm long, 550mm wide and 500mm high. Total weight is approximately 23kg.

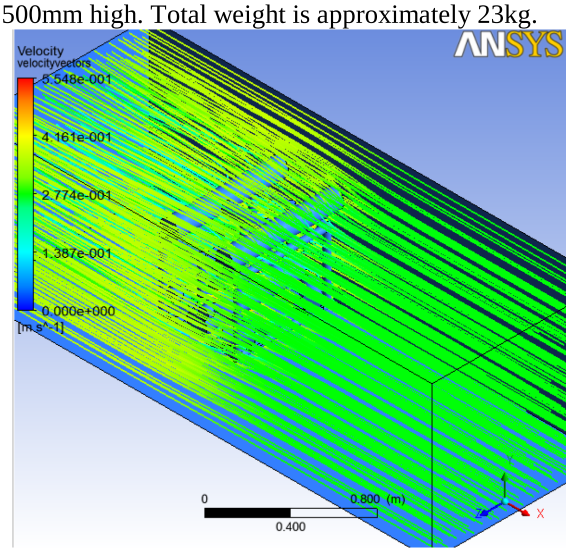


Figure 2: CFD analysis for drag forces

In addition, the evaluation of the drag forces is considered. Figure 2 shows the simulation result of fluid flow along the ROV by using the Computational Fluid Dynamics (CFD) software with a desired speed of 0.5 m/s. The drag force along the x-axis is 21.8 N, while the drag force along z-axis is 15.2 N. With the calculated drag force, motors are chosen accordingly with appropriate power and velocity. The vehicles behavior during acceleration will not be predictable because the proposed approach is based only on constant speeds. This would provide initial information to calculate the required power for the ROV's thrusters.

Buoyancy and stability

ROV will float or sink depending upon the net effect of the weight of the object and the buoyant force generated by the object. Buoyant force is determined by equation:

$$F = \rho.g.V$$

Where

ρ: density of the displaced fluid

g: acceleration due to gravity, $g = 9.81\ m/s^2$

V: volume of the displaced fluid

Three possible conditions for the object:

- Positive buoyancy: buoyant force > weight, the object floats
- Neutral buoyancy: buoyant force = weight, the object neither floats nor sinks.
- Negative buoyancy: buoyant force < weight, the object sinks.

The main component of buoyancy system is consists of two tanks which make from PVC pipes.
Stability of an ROV is affected by the distance between the center of gravity and the center of buoyancy. We calculate suitable parameter in order to ROV can float hang in water and remain self-stabilized.

Electric Design:
Sensor
In order to control ROV accurately, we need feedback signal from the sensors. This ROV is equipped with gyroscope, accelerometer, compass, pressure sensors for performing underwater movements. We use MPU6050 sensor which combine a 3-axis gyroscope and a 3-axis accelerometer to provide a full 6 degree-of-freedom motion tracking system. The compass sensor is a 3-axis digital magnetometer IC designed for low-field magnetic sensing. Pitch and heading angle is read from sensor and computed by Kalman filter. For pressure measurement, the sensor MPX4250AS is used. With the data obtained from it, we can convert it into depth information.

Driver DC motor, microcontroller.
Microcontroller need to have high processing speed, large capacity and low power consumption.

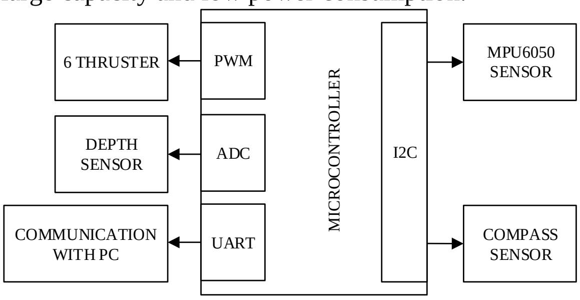


Figure 3: A block diagram of the central control

We choose the STM32F4 Discovery kit which meets those requirements.
Motor driver module is based on L298N H-bridge which is a high current, high voltage dual full bridge driver manufactured by ST Company. It can drive up to 2 DC motors at 2A each. The driver can control both motor RPM and direction of rotation.

Power and communication with PC
Control commands and sensor feedbacks are transferred using RS485 bus. Communications between the operator and ROV shall be maintained at all times.

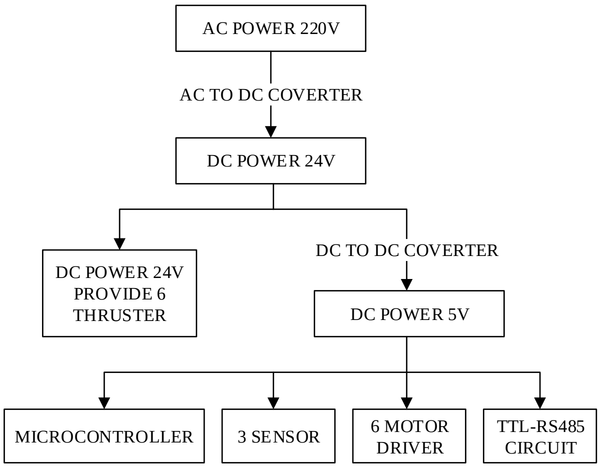


Figure 4: A block diagram of the power's ROV

The AC power source is converted on the surface or on the vehicle itself and then distributed to separate bus circuits to provide the necessary power to various components.

ROV model:
The ROV model is composed of three main components: the rigid body, the propeller and the DC motor. The rigid body model is derived from the Newton-Euler formulation. The Newton-Euler formulation is based on New-ton's Second Law and concerns the conservation of both linear and angular momentum.
It is important to consider two coordinate frames: the body-fixed and the earth-fixed. The body-fixed is attached to the vehicle. Its origin is normally fixed on the center of gravity. The motion of the body-fixed reference frame is described in relation to the earth-fixed reference frame. The earth-fixed reference frame can be considered inertial for low velocity vehicles such as ROVs.
Position and orientation (earth-fixed):

$$\eta = [\eta_1 \ \eta_2]^T = [x \ y \ z \ \phi \ \theta \ \psi]^T$$

Where x, y, z represent the Cartesian position in the Earth-fixed frame and ϕ represent the roll angle, θ the pitch angle and ψ the yaw angle.
Linear and angular velocity (body-fixed):

$$v = [v_1 \ v_2]^T = [u \ v \ w \ p \ q \ r]^T$$

Where u, v, w respectively with linear velocity in surge, sway, heave; p, q, r respectively with angular velocity in roll, pitch, yaw.
The velocities in both reference frames are related through the following transformation which is based on the Euler angles:

$$\dot{\eta} = \mathrm{J}(\eta)v$$

Where

$$\begin{bmatrix} \dot{\eta}_1 \\ \dot{\eta}_2 \end{bmatrix} = \begin{bmatrix} \mathrm{J}_1(\eta_1) & 0_{3\times3} \\ 0_{3\times3} & \mathrm{J}_2(\eta_2) \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \end{bmatrix}$$

Thus, τ are the forces and moments applied on the vehicle in body fixed coordinates.

$$J_1(\eta_1) = \begin{bmatrix} cos\psi\, cos\theta & -sin\psi\, cos\phi + cos\psi\, sin\theta\, sin\phi & sin\psi\, sin\phi + cos\psi\, cos\phi\, sin\theta \\ sin\psi\, cos\theta & cos\psi\, cos\phi + sin\phi\, sin\theta\, sin\psi & -cos\psi\, sin\phi + sin\theta\, sin\psi\, cos\phi \\ -sin\theta & cos\theta\, sin\phi & cos\theta\, cos\phi \end{bmatrix}$$

$$J_2(\eta_2) = \begin{bmatrix} 1 & sin\phi\, tan\theta & cos\phi\, tan\theta \\ 0 & cos\phi & -sin\phi \\ 0 & sin\phi/cos\theta & cos\phi/cos\theta \end{bmatrix}$$

In the body-fixed frame the nonlinear equations of motion are:

$$M\dot{v} + C(v)v + D(v)v + g(\eta) = \tau$$

Where:

- $M = M_{RB} + M_A$ is the inertia matrix for rigid body and added mass, respectively;
- $C(v) = C_{RB}(v) + C_A(v)$ is the coriolis and centripetal matrix for rigid and added mass, respectively;
- $D(v) = D_{quad}(v) + D_{lin}(v)$ is the quaudratic and linear drag matrix, respectively;
- $g(\eta)$ is the hydrostatic restoring force matrix;
- τ is the thruster input vector.

Control algorithm:

The movement of ROV in the water is achieved by cooperation of propeller system and control surfaces. For effective control of the motion of ROV in 6 DOF, we need to design suitable controllers. If the controllers are designed based on the whole model, it will be difficult to obtain the desired performance. According to the 2 purpose consist of depth control and heading control, we separate the whole dynamic model into 2 subsystems which correspond purposes respectively. Based on each subsystem, we design a controller.

Despite the extensive range of controllers, in practice most industrial underwater robots use Proportional Integral Derivative (PID) controller, thanks to their simple structure and effectiveness under specific condition. Equation describes PID controller:

$$O_{PID} = K_p e + K_i \int edt + K_d \frac{de}{dt}$$

In some case not all three terms are necessary to meet the control requirement of each DOF and to set the gain values to zero. Parameters of PID controller are determined by trial and error method.

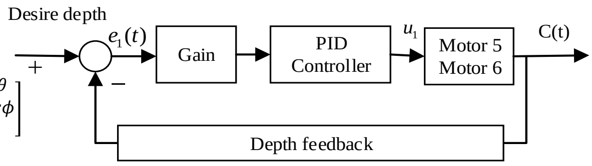


Figure 5: Depth control system block diagram

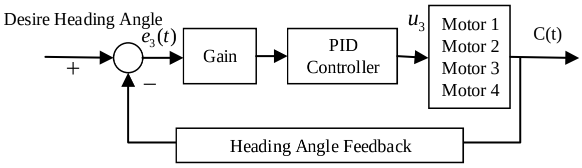


Figure 6: Heading control system block diagram

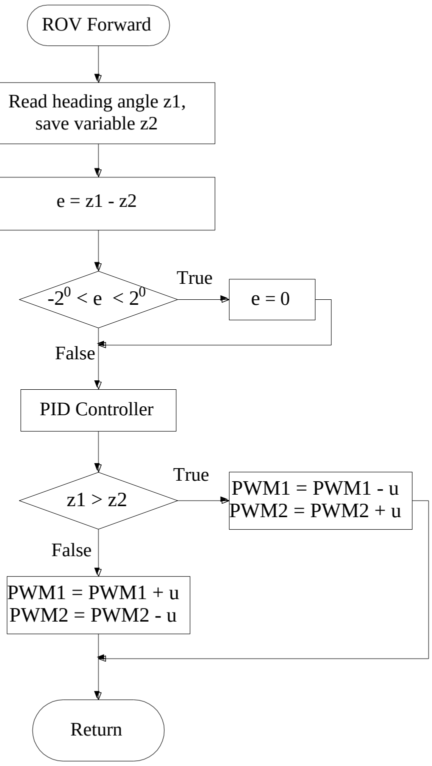


Figure 7: ROV Forward Function

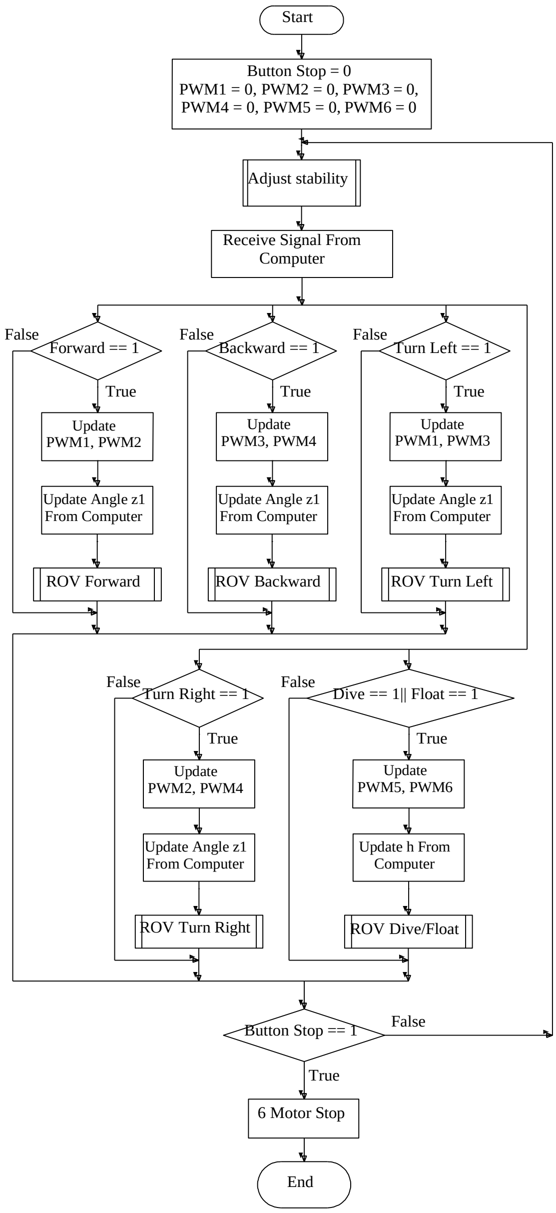


Figure 8: Control algorithm

Software control ROV

The program is written on visual studio C# 2013. The program receives and displays feedback signal from sensor, concurrently it sends control commands to microcontroller.

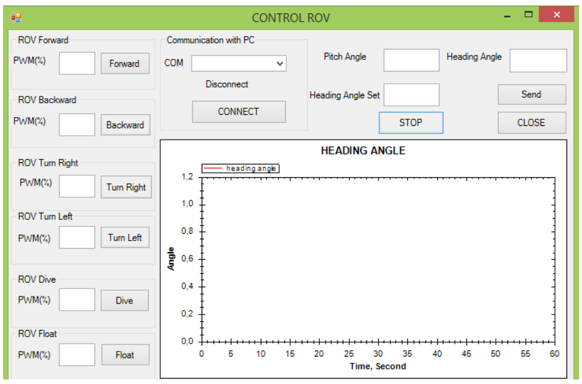


Figure 9: Program control ROV

Results and Discussion:

ROV is able to submerge into 5 meter below the water without any leaking problem in main body and protective frame. 3 test of basic motion controls were conducted with the desired angle heading, rotating 90^0, diving to 1m. Each experiment was repeated a number of times to determine suitable parameter of PID controller. In other words, the gain of a PID controller can be obtained by trial and error method. The response of the algorithm for attaining the set value is recorded and shown in figure 10, figure 11 and figure 12.

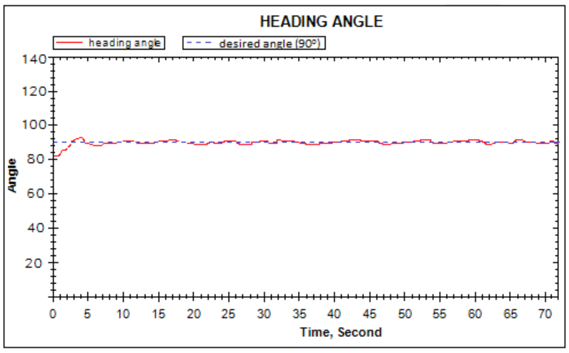


Figure 10: ROV runs forward with desired angle = 90^0

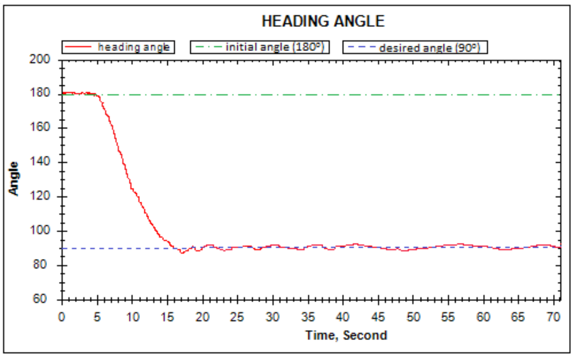


Figure 11: ROV rotates 90^0

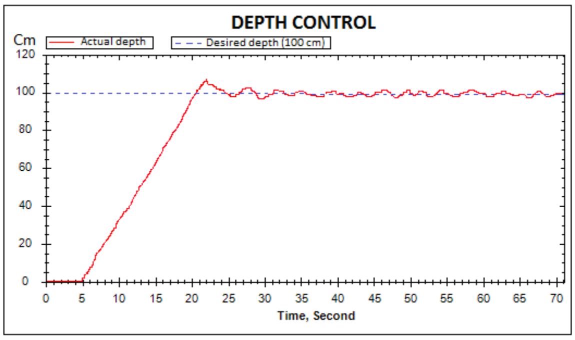


Figure 12: ROV dives 1m

The figure 10 shows the response of heading angle when ROV runs forward with desired angle 90^0 and its initial angle is 82^0, time response is 2.5s and maximum error in this case is $\pm 2^0$. Similarly, in the figure 11, when its initial state is 180^0, it rotates to the right 90^0, response time is 10.5s and maximum error is $\pm 2^0$, the change of angle is nonlinear. In the figure 12, with the positive z-axis pointing down and intital position of ROV is selected as origin of coordinate, the graph shows the response of the depth when ROV dives 1 meter (from 0m to 1m). In this case, maximum error less than 0.05m and response time is 18s. Experimental results meet the initial requirements and control agorithum is suitable.

Conclusion:

This paper has shown design, actual model and method to control ROV. In the part of mechanical design, optimal thrust allocation has been proposed by equation. Low cost material (PVC pipes) was mainly used for constructing the body to reduce the cost and weight. Signals feedback from sensor combine with PID controller to maintain stability, control direction and depth. After several experiments have been successfully done in a pool and parameters of PID controller are suitably chosen, the ROV can move to desire depth and response of the heading control is satisfactory maintaining heading within $\pm 2^0$. In the future, we will equip camera to observe, reduce weight and increase operating depth.

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