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Research Article

Study on analysis and design of an VIAM- AUV2000 Autonomous Underwater Vehicle (AUV)

Tran Ngoc-Huy*, Chau Thanh-Hai

ABSTRACT

This paper presents the design of the VIAM-AUV2000 autonomous underwater vehicle (AUV) with a built-in cylinder for floatation and counterbalance. The modular structure including mechanical design, electronic system, and control algorithm ensures continuous operation for the vehicle at a depth of 50 meters underwater. The main content will consist of two parts: the mechanical implementation and the electrical system. The mechanical implementation part will focus on calculating ship hull profile and material selection; computing and simulating stress and distortion on ship hull and waterproof covering using finite element method with NX Nastran; analyzing and planning cylinder and counterbalance arrangements. At the same time, the advantages of hybrid AUV design inspired from the traditional one with thruster and fins as well as the underactuated glider form using counterbalance and cylinder for diving and floating are discussed specifically in the upcoming sections. The electrical system for the robot is also mentioned and clarified through the selection of sensors, actuators and hardware design to ensure stable operation for diving robot at a depth of 50m and operate continuously for long periods under water by using traditional AUV mode and glider mode. Some experimental results of thruster and three-axis tilt estimators with error of less than 1^o are also presented in this paper.

Key words: AUV, FEM, diving/floating mechanism, thruster, tri-axis rotation angles estimator

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INTRODUCTION

Nowadays, along with the rapid revolution of humankind, science and technology become more modern day by day, we gradually explore and conquer the mysteries of nature. However, the ocean is still a mystery far away from our reach and understanding. The research of ocean, decryption of the mystery in the deep of the sea required modern technology such as unmanned underwater vehicles, which can swim in the deep that no human can reach. In order to investigate the water environment, examine the ecosystem, probe the environmental fluctuation, or use for the military purpose, national defense, and observation… many prototypes of AUVs have been researched and developed. AUV Remus 100 of Woods Hole Oceanographic Institution[1] can dive to 100 meters in more than 10 hours at the velocity of 2.3 m/s. Lightweight AUV[2] developed by Porto University in cooperation with OceanScan work at 20 meters depth in 8 hours at 1.5-2m/s. Autosub6000 of Autonomous Underees Vehicle Applications Center can dive to 6000 meters in 30 hours at 5km/h. Slocum Glider without thruster can work in several months[3]. Vietnam is a coastal country with more than 3.200 kilometers of coastline, and the sea area is about 1.000.000 square kilometers. Economic, scientific, tourism activities and national defense that take place on the sea are playing a very important role. Nowadays, many constructions are built on the sea such as ports, oil platforms, oil and gas pipelines, etc. At the same time, the arising of critical demand for surveying the topography and environment deep down the water surface as well as maintenance and equipment inspection. In the military, the demand for observation and mine removal also experience great increasing… That why the research and development of devices working underwater is one of the most important missions in order to take advantage of the sea and marine resources.

This paper will focus on the design of AUV hull using Finite element analysis to determine the suitable thickness of hull's part; design the diving and floating mechanism; and design the control system for AUV.

METHODOLOGY OF DESIGN

Design Ideas

Design specifications:

- Torpedo shape
- Maximum depth: 50 meters
- Maximum velocity: 2 meters per second
- Time of continuous working: 2 hours

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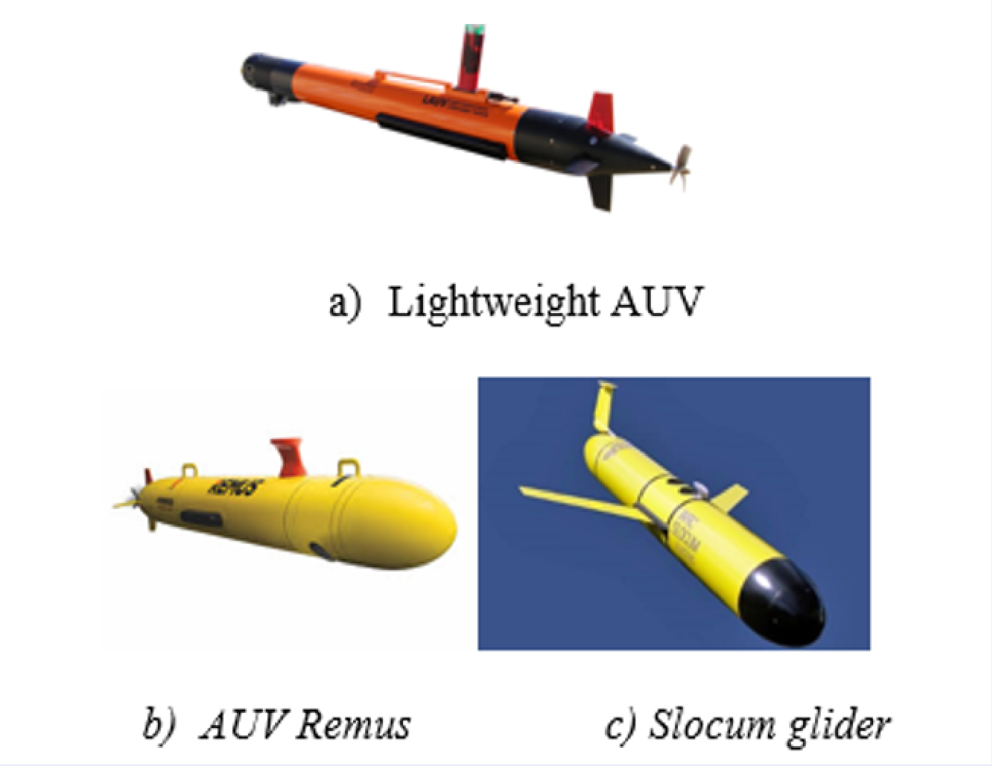
a) Lightweight AUV

b) AUV Remus

c) Slocum glider

Figure 1: AUV with torpedo shape

- Maximum weight: 70 kilograms

The design idea for diving/floating mechanism has been integrated into five design plans (1 – 5) which shown in Figures 2, 3, 4, 5 and 6. Where[4]:

1: VIAM-AUV2000's head
2: VIAM-AUV2000's body
3: VIAM-AUV2000's tail
4: Cylinder (Figure 4)
5: CounterWeight (Figures 2 and 4)
6: Control board (Figure 3)
7: Battery (Figure 3)
8: Cylinder (Figures 3 and 6)
9: Stern wing (Figures 3 and 6)
10: Thruster (Figure 3)

Those design plans are considered by using the decision matrix[5], with plan 1 is chosen to be the standard for comparison.

From the result of Table 1, our team decided to choose plan 4: diving/floating mechanism using one cylinder and counterweight (Figure 5).

Design Of Shape And AUV Hull

Almost torpedo shaped AUV based on Myring shape (Figure 7) with the cylinder body, the head and stern will be designed according to formula (1) and (2)[6].

Head's shape:

$$r_{(x)} = \frac{1}{2}.d.\left[1-\left(\frac{x-a}{a}\right)^2\right]^{\frac{1}{n}} \qquad (1)$$

Stern's shape:

$$r_{(x)} = \frac{1}{2}.d - \left[\frac{3d}{2c^2}-\frac{\tan\theta}{c}\right].(x-a-b)^2 + \left[\frac{d}{c^3}-\frac{\tan\theta}{c^2}\right].(x-a-b)^3 \qquad (2)$$

Where:

$r_{(x)}$: radius of section at position x.

d: the maximum of diameter at the cross-section.

a, b, c: length of head, body, and stern of AUV.

θ: angle at the end of the stern.

n: parameter of the head's shape.

Parameters for designed AUV shape included a, b, c, n, θ is shown in Table 2[7].

Base on AUV prototypes that have been built in the world and the other underwater vehicles, especially vehicles work in the sea environment, we decided to use Aluminium Alloy T6 – 6061 with mechanical properties shown in Table 3[7].

Using finite element method (FEM) with NX Nastran apply for AUV hull, 4mm thickness, 800mm length, 250mm outside diameter, two end fixed by the flange, the pressure at 50m depth is 0.5MPa. The result in Figure 8 show that the maximum stress on AUV hull

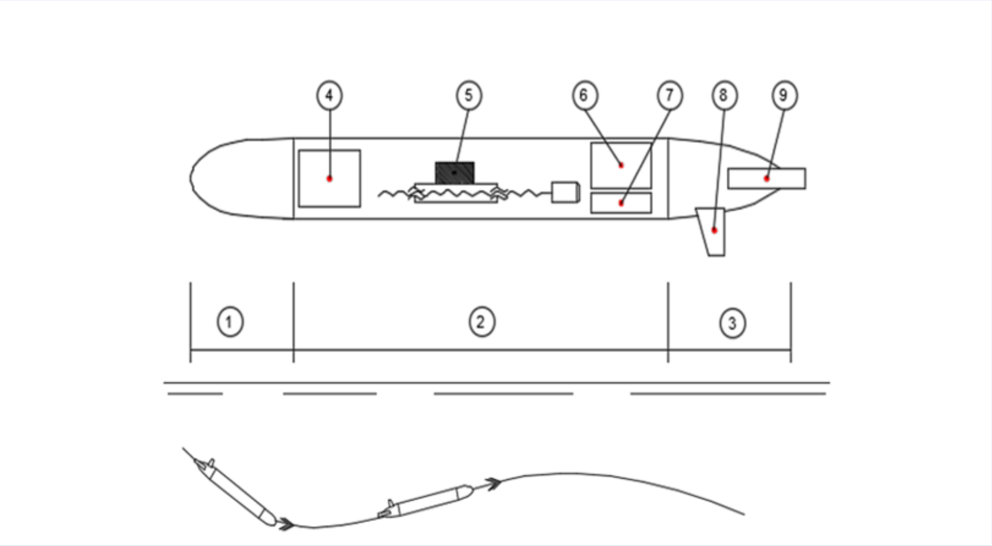

Figure 2: Diving/floating mechanism using a counterweight.

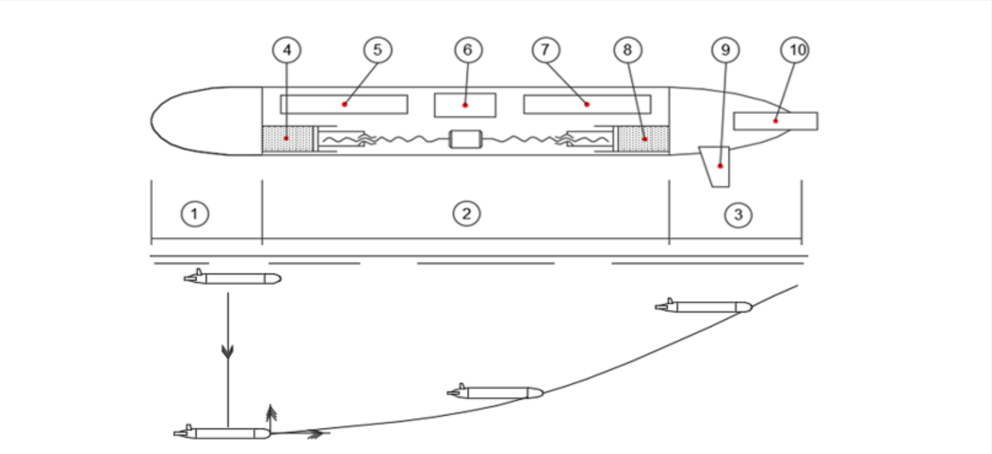

Figure 3: Diving/floating mechanism using two cylinderscontrolled by one motor

Table 1: Decision matrix for design plans

Plan Standard	1	2	3	4	5
Easy for manufacturing	0	-	-	-	-
Easy for assembly and maintenance	0	-	-	-	-
Simple in control	0	0	-	+	-
Flexible	0	-	+	+	+
Good arrangement	0	0	-	+	-
Balance	0	-	+	+	+
Total Score	0	-4	-2	2	-2
Decision	No	No	No	Yes	No

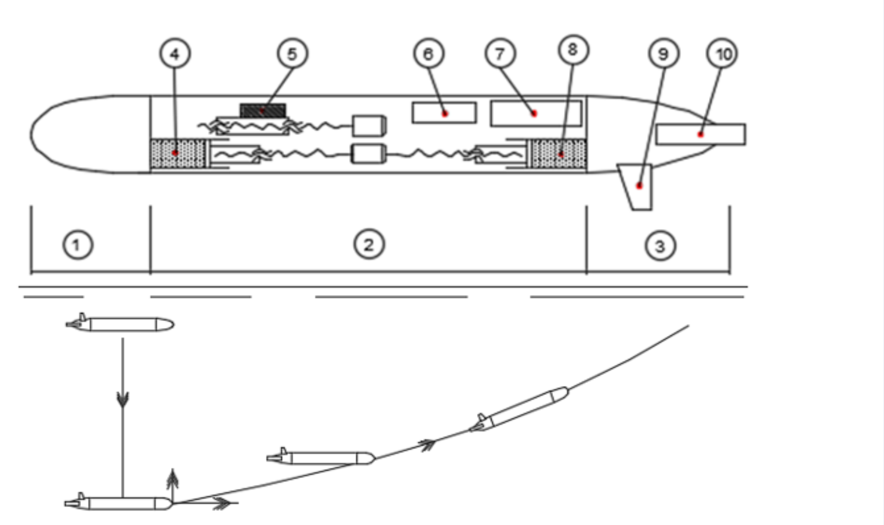

Figure 4: Diving/floating mechanism using 2 cylinderscontrolled by one motor and counterweight

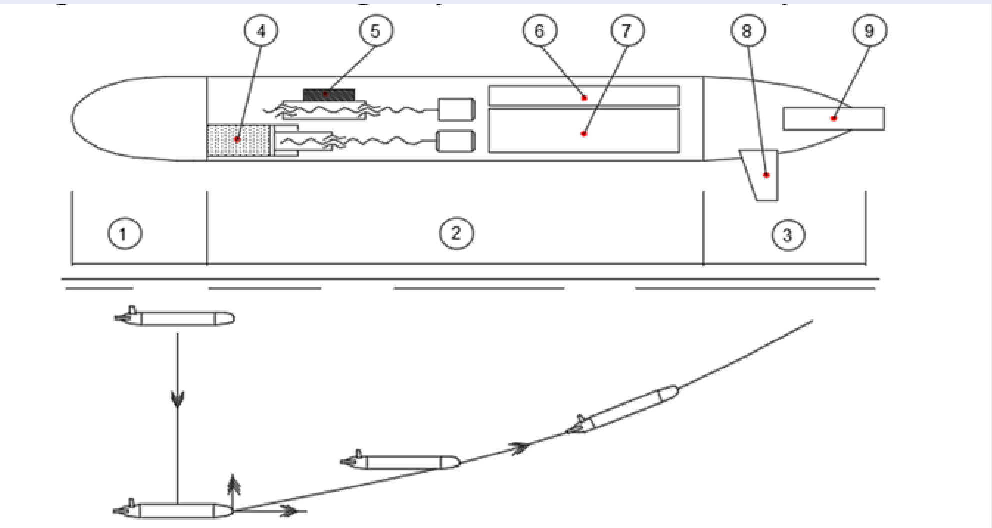

Figure 5: Diving/floating mechanism using one cylinder andcounterweight

Table 2: Parameters of AUV's shape

Parameters	Value
a	300 mm
b	1400 mm
c	330
d	250 mm
n	2
θ	25^o

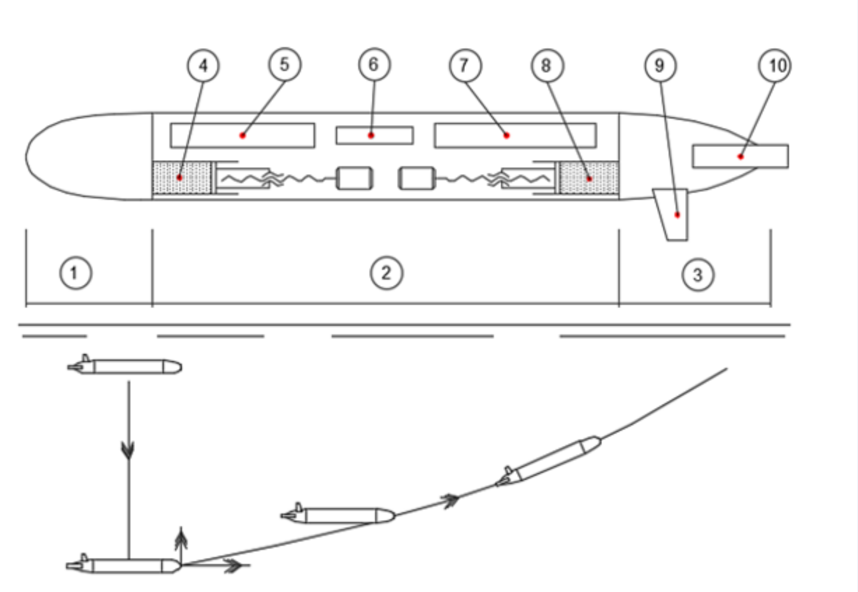

Figure 6: Diving/floating mechanism using 2 independentcylinders

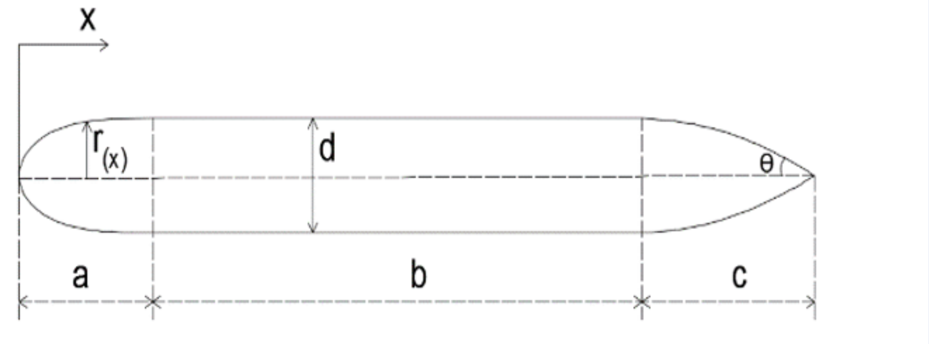

Figure 7: Myring shape

Table 3: Aluminium Alloy T6-6061 mechanical properties

Ultimate tensile strength (MPa)	Tensile yield strength (MPa)	Drag race	Thermal conductivity (BTU hr.ft.°F)
$\geq$310	$\geq$ 270	10%	1160

is 14.94 MPa << $[\sigma_c]$ = 275 Mpa and maximum displacement is 0.0287mm.

Using FEM apply for AUV flange with 3, 4, 6 mm thickness, the result is shown in Figure 9, and Table 4. The flange with 6mm thickness is the most suitable for AUV body. However, with the demand for setting up other components, AUV flanges have to bear lots of loads, such as the mass of components inside AUV,… By optimizing the structure of the flange and using FEM, we got the structure of the particular flange shown in Figure 10. The Figure 10 also indicates the maximum stress and displacement, which is 48,84Mpa and 0.0577mm respectively.

Design Of Diving/Floating Mechanism

Piston-cylinder pump

Figure 11 shows structure of Piston-cylinder 3D model. Axial force acting on the cylinder is calculated with formula (3) include friction force between O-ring and cylinder wall (4), water pressure acting on the piston (5), pneumatic pressure while piston mov-

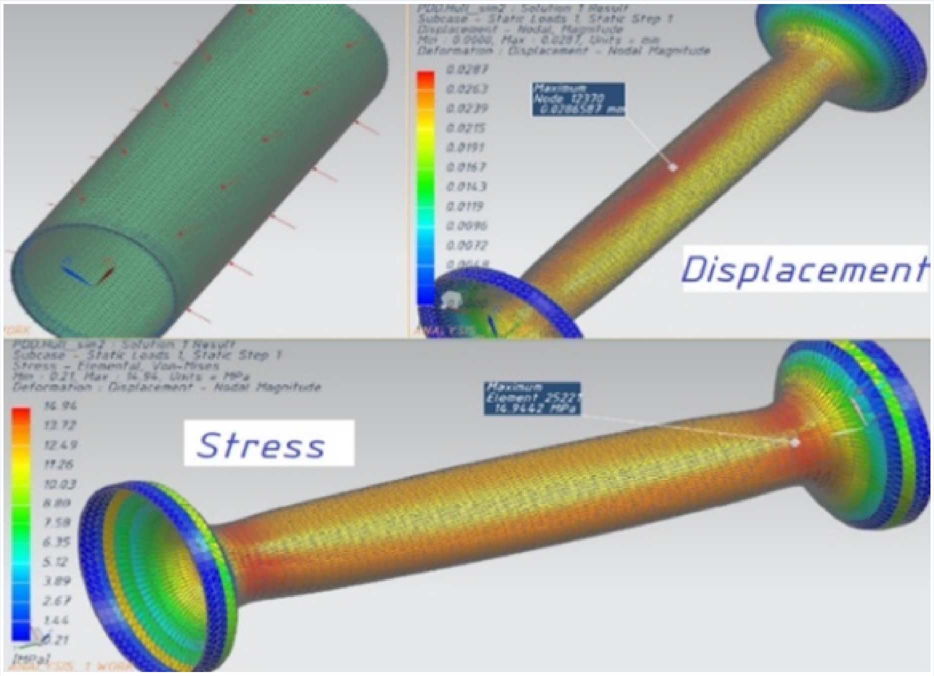

Figure 8: Finite element analysis for AUV hull.

Table 4: Value of maximum stress and displacement on AUV hull

Thickness (mm)	Maximum stress (MPa)	Maximum displacement(mm)
3	175.8	0.626
4	125.8	0.489
6	65.94	0.242

ing (6).

$F_a = F_p - F_{ms} - F_n$ (3)

The friction force between the O-ring cylinder wall:

$F_{ms} = F_c + F_h$ (4)

Where:

$F_c = f_c.L_p$ is the friction force created by the compression the O-ring:

f_c: friction force acting on 1cm length [N/cm]

L_p: Length of O-ring

$F_h = f_h.A_p$ is the friction force created by contact surface of the O-ring and the cylinder wall:

f_h: friction force acting on 1cm^{2}area of the contact surface.

A_p: area of the contact surface.

Axial load F$_p$ created by water pressure (Figure 12):

$F_p = p.A_{piston}$ (5)

Where:

p: Water pressure.

- Apiston: area of the piston

Pneumatic pressure:

$F_n = \frac{P_2}{A_p}$ (6)

Let assume that the process is isothermal:

$P_1V_1 = P_2V_2 \Leftrightarrow P_2 = \frac{P_1V_1}{V_2}$

The preliminary diameter of ballscrew is calculated with formula (7)[7].

$d_1 \geq \sqrt{\frac{4x1,3.F_a}{\pi.[\sigma_k]}}\ (mm)$ (7)

Where $[\sigma_k]$: tensile yield strength of the material.

Torque on ballscrew:

$T = \frac{F_aP_h}{2\pi\eta_1}\ (Nm)$ (8)

Lead angle:

$\gamma = arctg\left[\frac{p_h}{\pi.d}\right]\ (^o)$ (9)

Where

- P$_h$: pitch (mm)
- η_1: efficiency (%)

The overall parameters of the cylinder's ballscrew are shown in Table 5.

Overall efficiency:

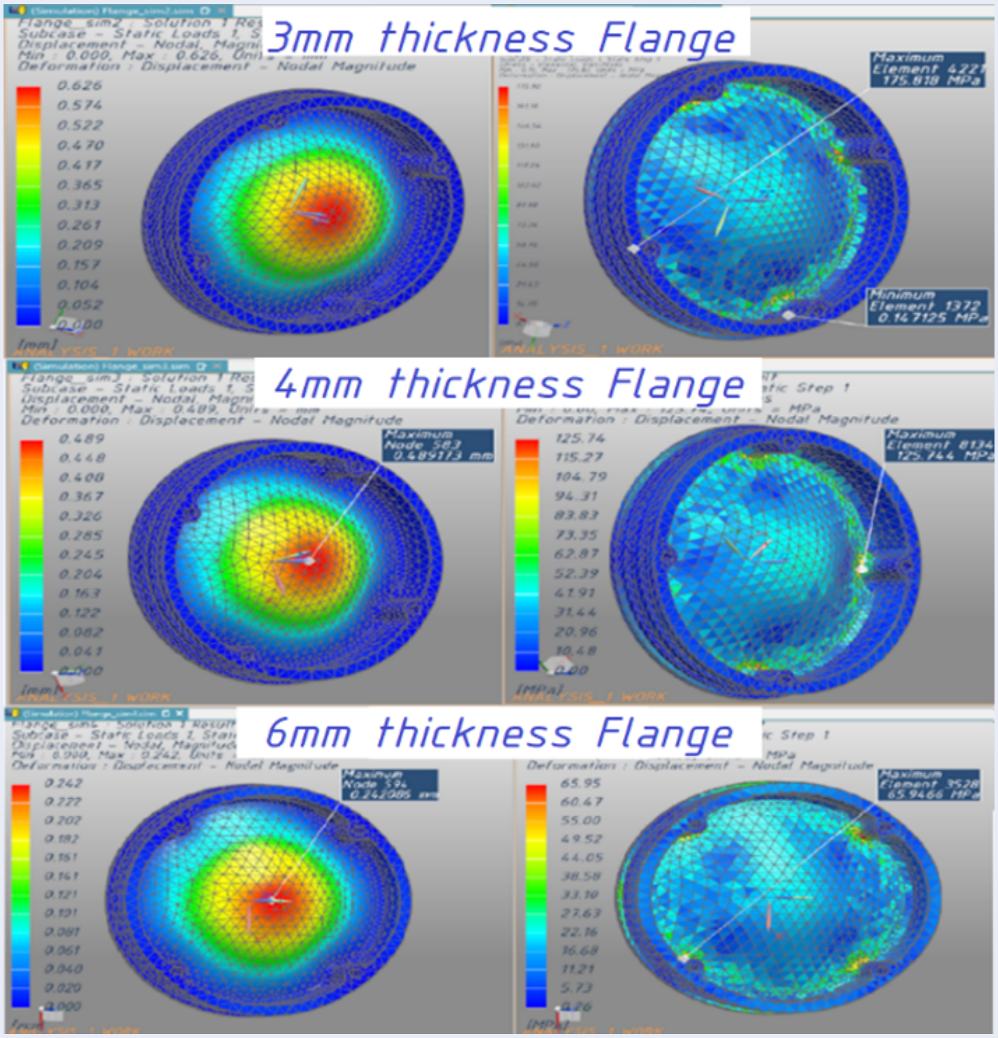

Figure 9: Displacement (left) and stress (right) ondifferent thickness AUV flange

Table 5: Parameters of cylinder's ballscrew

p (mm)	d_1 (mm)	N (rpm)	Fa (N)	T (Nm)	P (W)
10	10	60	2187	3.55	22.31

$$\eta_{ch} = \eta_{motor}.\eta_{gearbox}.\eta_{belt}.\eta^2{}_{bearing}.\eta_{cv}^2 = 0,8 \times 0,7 \times 0,95 \times 0,99^2 \times 0,95^2 \simeq 0,47 \qquad (10)$$

The required motor capacity:

$P_{đc} = 22.31/0.47 \simeq 47.5$ W

For the cylinder system, use MAXON motor EC-I 52ϕ52mm, brushless, 180W (Part number 574741), maximum torque T_{max}=12.2Nm, N = 4720 rpm, and planetary gear box GP 52 C ϕ52, with transmission ratio 81:1.

Counterweight

Counterweight includes 8 round battery with is 310g/battery (Figure 13), linear bearing, $P_{counterweight} \simeq$ 3kg

After considering (7), (8), (9) and standard specification selection, the parameters of counterweight's ballscrew is shown in Table 6. The axial load F_a is calculated while AUV swimming in the glider's journey (Figure 14). Let assume that $F_a \simeq P_{counterweight}$ = 30N. For the counterweight, Faulhaber 2444 motor 51W would be use for counterweitght with some specification such as aximum torque 18mNm, 45000rpm, and

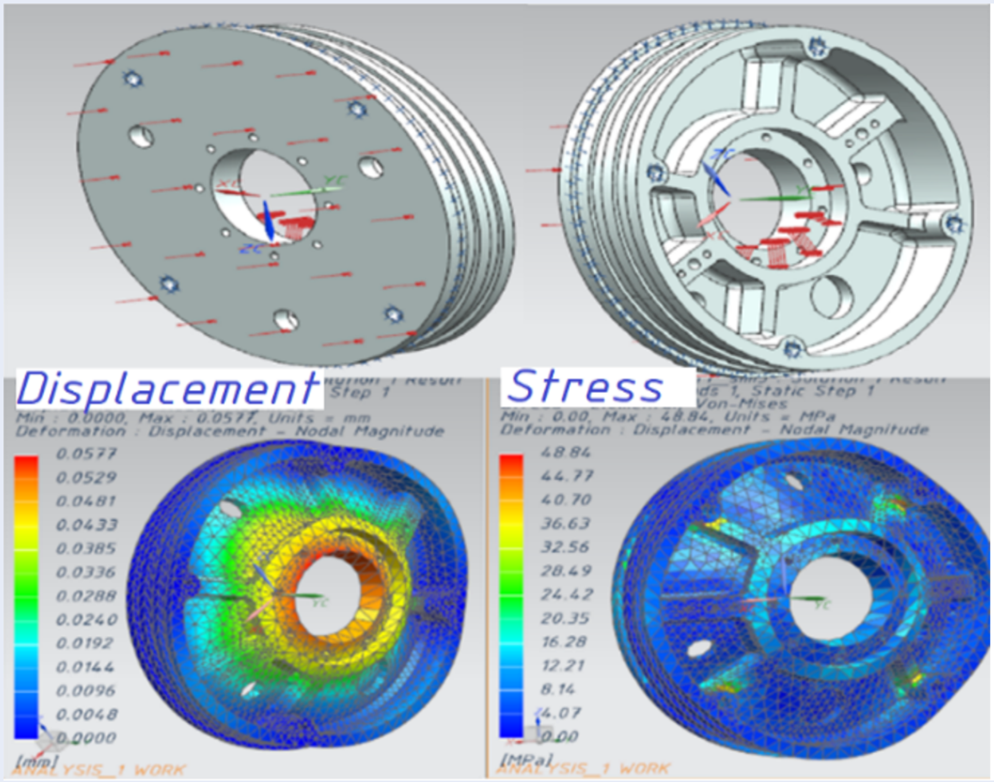

Figure 10: FEA of designed AUV flange

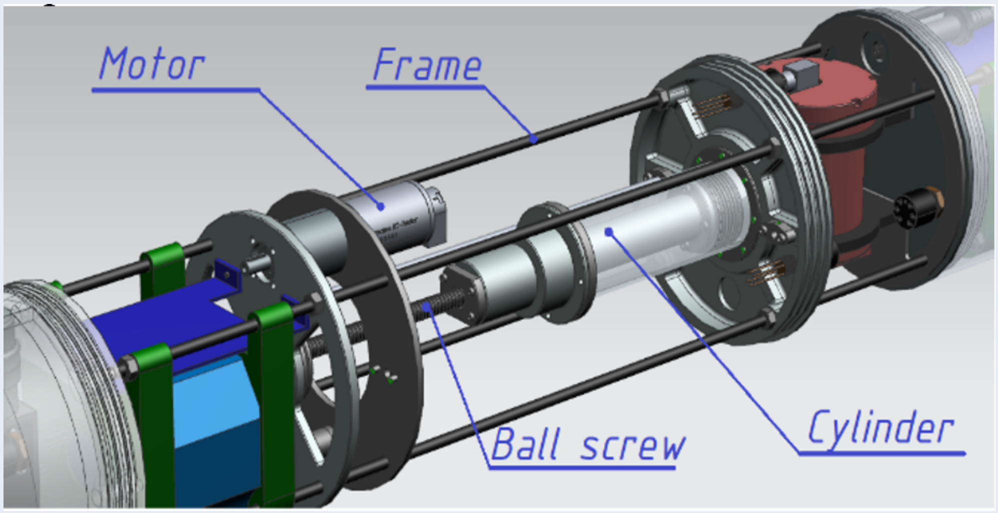

Figure 11: Piston-cylinder 3D model

Table 6: Parameters of counterweight's ballscrew

p (mm)	d_1 (mm)	N (rpm)	Fa (N)	T (mNm)	P (W)
4	10	150	30	20	0,3

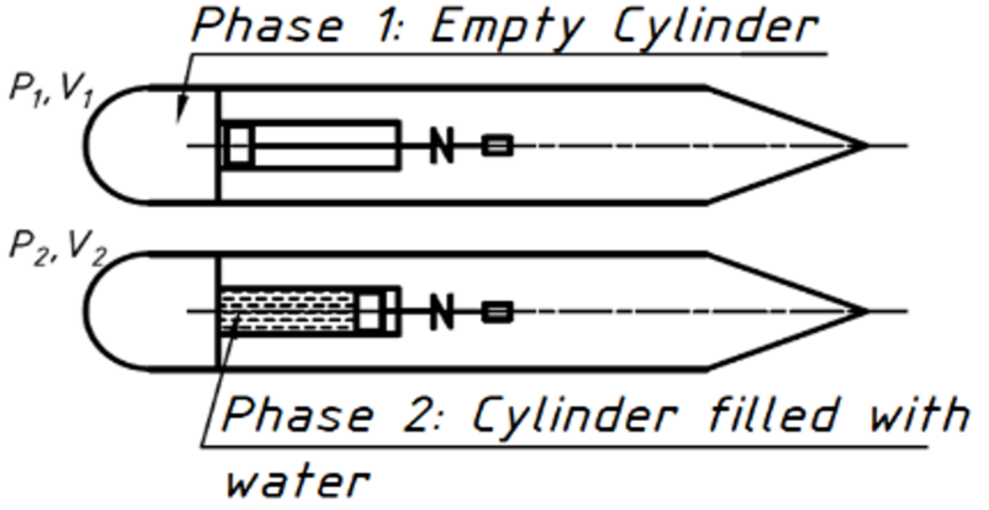

Figure 12: Cylinder status

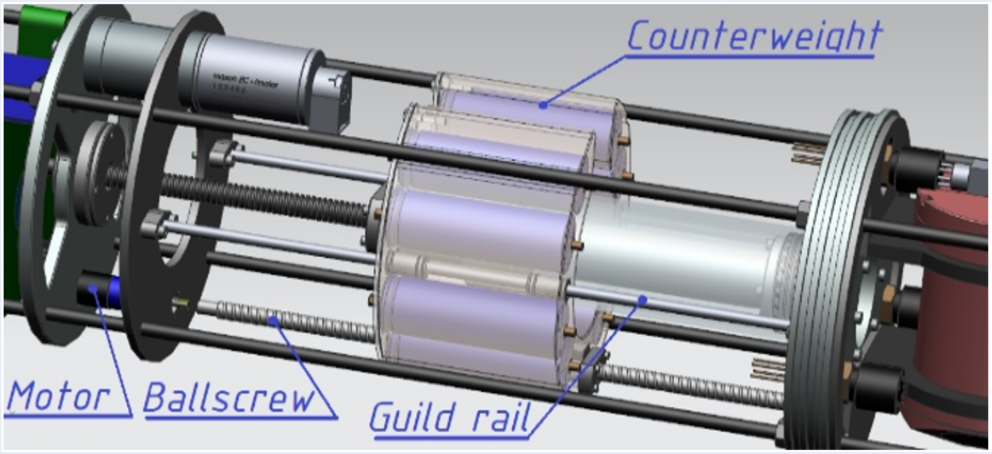

Figure 13: Counterweight 3D model

planetary gearbox 23/1 with transmission ratio 43:1, maximum torque 0,7Nm.

Figure 15 shows the overall structure of the AUV and layout of the sensors.

Design and manufacture thruster

The thruster was designed using a magnetic couplingas shown in Figure 16 with specifications Table 7 [8]:

Figure 17 (above) depicts the relationship between speed and current of the thruster. Considering the motor speed of 1000 rpm, the circuit still withstands 10A currents because of its good heat dissipation. Figure 17 (below) show that the thruster is stable and less noise. At 1000 rpm, the thrust of the engine was able to reach more than 6 kgf corresponding to 55% of the motor's power output.

METHIDOLOGY AND RESULTS OF THE ELECTRICAL SYSTEM

The robot is connected to the control center located on the surface (on the shore, on the mothership,…), data will be transmitted to the central station for management and command control via RF wireless system, GSM/GPRS, and Sonar.

The electrical system structure of the AUV is shown in Figure 18. The high-performance central processing unit allows the AUV to process received data at high speed, creating a premise for the AUV applies the advanced algorithms of guidance and control to serve

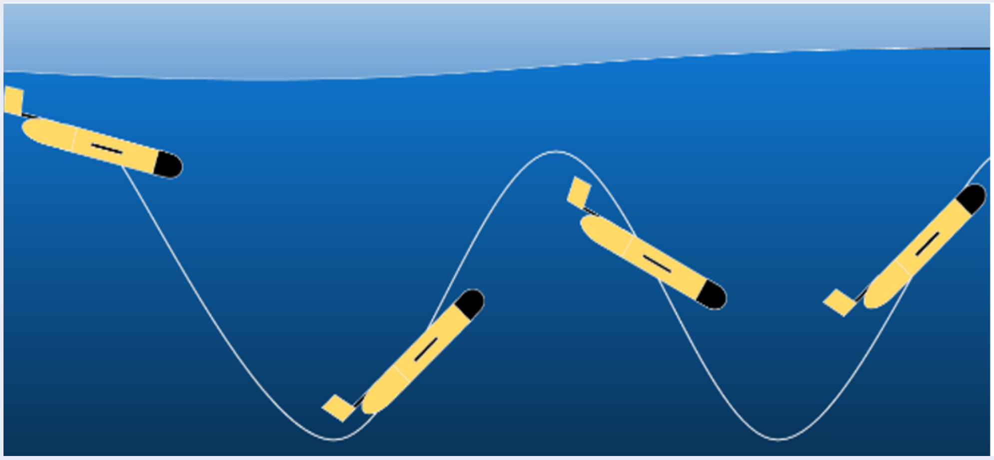

Figure 14: Glider

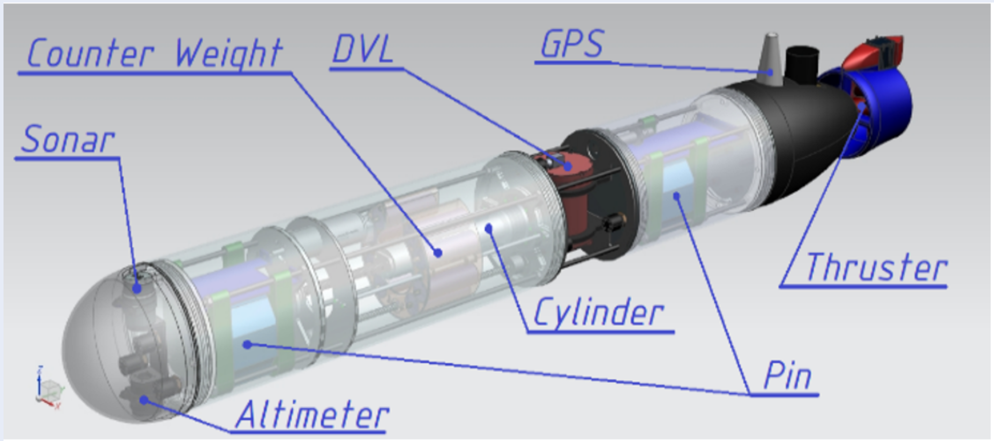

Figure 15: Completed 3D model of AUV

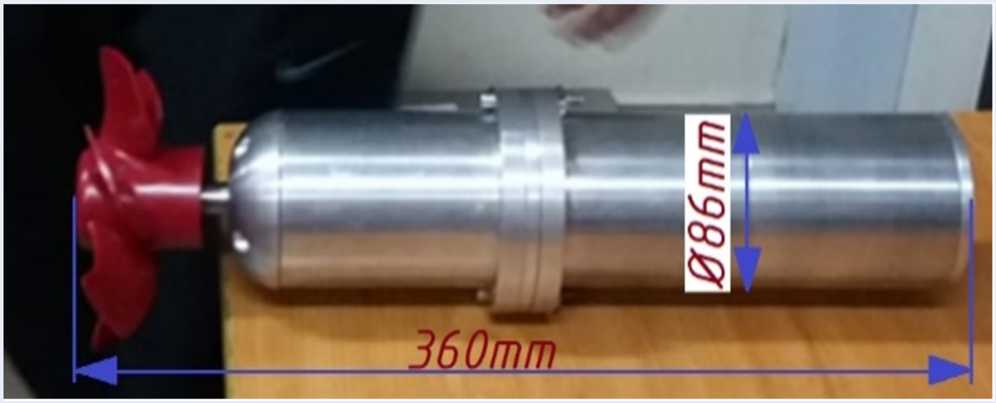

Figure 16: Thruster of AUV-VIAM2000

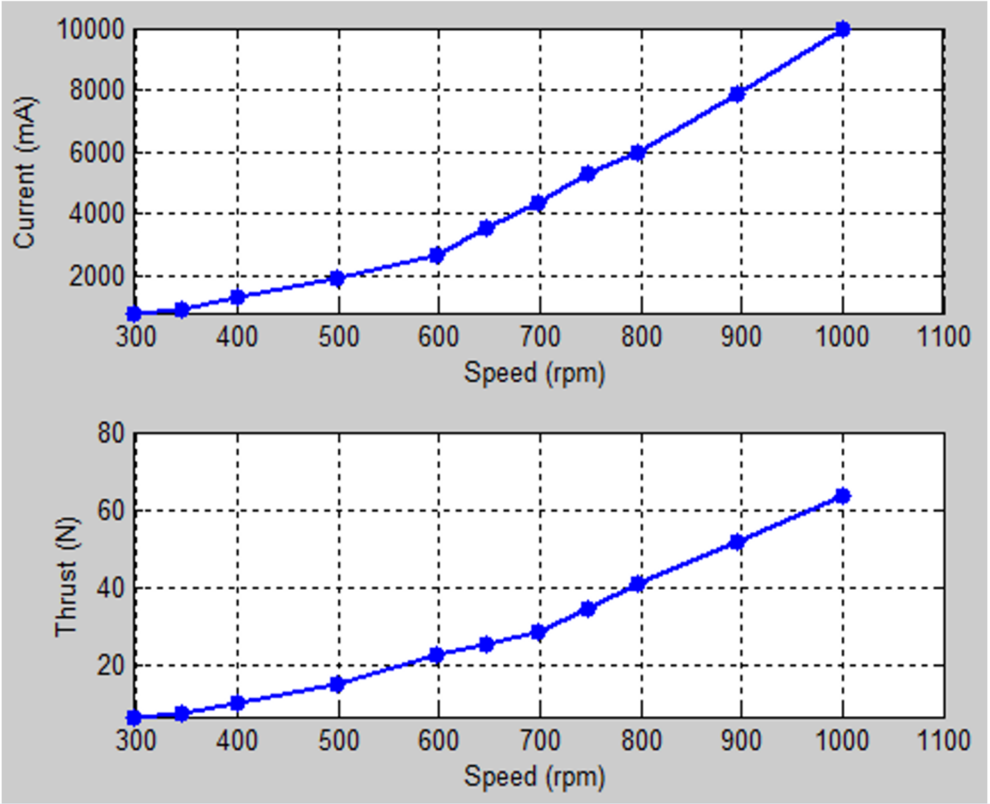

Figure 17: BLDC Motor Current/Speed andThrust/Speed Curves

Table 7: Specifications of thruster

Type	Brushless DC
Size (mm)	L360mm x D86mm
Power (W)	600
Speed (rpm)	1850
Depth rate (m)	100
Max. thrust (kgf)	8
Number of wings of the propeller	6
Power supply (Vdc)	48
Communication	CANBUS

each specific operating requirement. Data acquisition systems from sensors and actuator controllers are designed using high-speed ARM core microcontrollers (STM32Fx), which are interconnected via the CAN communication standard with a transfer rate of up to 1Mbit. The robot is equipped with a variety of sensors to collect information of the operating state of the robot and the surrounding environment, thereby assisting the robot to make precise control decisions. The sensor system includes: GPS sensor (error < 1m horizontal), DVL velocity sensor (error 1% ± 1 mm/s), altimeter sensor and depth sensor (pressure sensor). In addition, tri-axis rotation angles estimator as shown in Figure 19 with high accuracy (error < 2 degrees) integrated into the AUV.

The algorithm in the tri-axis rotation angles estimator consists of two layers, each with an extended Kalman filter. Table 8 shows the error of the system in the

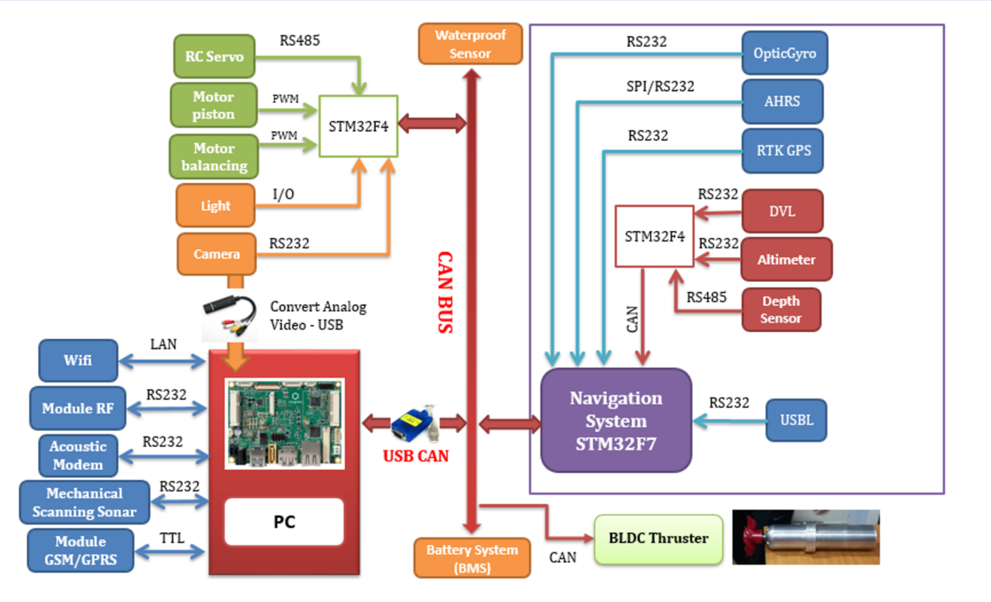

Figure 18: The electrical system of AUV-VIAM2000

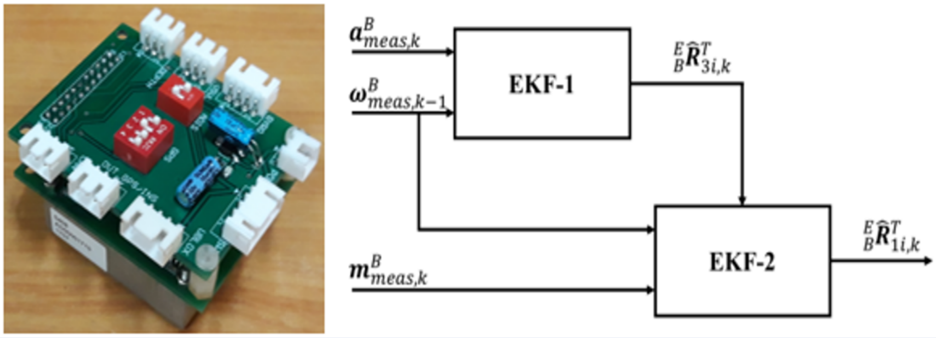

Figure 19: Tri-axis rotation angles estimator (left) andits algorithm (right)

Table 8: Results of the experimental error of the system

Experiment	RMS error (deg)		
	ϕ	θ	ψ
STATIC	0,4055	0,0989	0,2977
TURN_X	0,2640	0,2892	0,3077
TURN_Y	0,4324	0,3495	0,3278
TURN_Z	0,6066	0,6297	0,5540
TURN_XYZ	0,5103	0,5013	0,7047
STATIC_MAG_EXT	0,3729	0,3529	0,7769
TURN_Z_MAG_EXT	0,4903	0,5509	2,7880

static state, rotating around the x, y, z-axes, in the static state influenced by the external magnetic, and rotating around the z-axes influenced by the external magnetic.

DISCUSSION

The study has presented many designed options and selected the most optimal designed solution for the AUV-VIAM2000, which is from selecting the Myring shape to using a combination of counterbalance and cylinder structure to support floating/diving. Thus, this help the diving robot can operate flexibly in two modes: AUV and glider that will help save energy. We also used finite element method to compute, simulate stress and distortion on ship hull which is 5mm thickness, and waterproof covering. In addition, tri-axis rotation angles estimator implementation has been tested with error <2 degrees in many cases and integrated into the AUV-VIAM2000. The 600W thruster device that we designed to ensure movableness of AUV-VIAM2000.

CONCLUSIONS

This paper has analyzed and selected the complete design options for the AUV-VIAM2000, capable of diving/floating at a depth of 50m by a combination of cylinder and counterbalance. Through stress simulation, finite element analysis has been used to select materials and suitable shell thickness, ensuring that the robot can operate at a stable design depth. Last but not least, the research has achieved some goals in building electrical system comprising sensors and actuators selection, hardware design, thruster manufacture and control as well as tri-axis rotation angles estimator implementation.

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CONFLICT OF INTERESTS

The author declares that this paper has no conflict of interests.

AUTHORS' CONTRIBUTIONS

Tran Ngoc Huy has proposed the methodology and wrote the manuscript. Chau Thanh Hai implemented hardware configuration, experiments and wrote the manuscript.

ABBREVIATIONS

AUV: Autonomous Underwater Vehicle
FEM: Finite Element Method
DVL: Doppler Velocity Log
GPS: Global Positioning System
GSM: Global System for Mobile Communications
GPRS: General Packet Radio Service
CAN: Controller Area Network

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Bài Nghiên cứu

Phân tích và thiết kế robot lặn không người lái VIAM- AUV2000

Trần Ngọc Huy[*], Châu Thanh Hải

TÓM TẮT

Bài báo giới thiệu về thiết bị lặn không người lái (AUV) sử dụng cơ cấu lặn nổi tích hợp xylanh và đối trọng, được xây dựng theo từng module riêng từ thiết kế cơ khí, hệ thống điện cho đến xây dựng giải thuật điều khiển cho thiết bị để đảm bảo thiết bị hoạt động liên tục một thời gian dài ở độ sâu 20 mét nước. Nội dung chính sẽ trình bày tính toán biên dạng vỏ tàu; lựa chọn vật liệu vỏ; tính toán và mô phỏng ứng suất, biến dạng trên vỏ tàu và các nắp đậy chống thấm bằng phương pháp phân tích phần tử hữu hạn với module tích hợp trong phần mềm Solidworks; phân tích và lựa chọn phương án bố trí xy lanh - đối trọng. Đồng thời, bài báo này sẽ chỉ ra những ưu điểm nổi trội trong thiết kế lai tạo giữa dạng AUV truyền thống sử dụng thiết bị đẩy và bánh lái để xoay chuyển và dạng glider sử dụng cơ chế đối trọng và xylanh hút nhả nước để lặn nổi. Ngoài ra, việc thiết kế hệ thống điều khiển cho robot cũng được đề cập và làm rõ thông qua lựa chọn thiết bị cảm biến, cơ cấu chấp hành và thiết kế phần cứng để đảm bảo khả năng hoạt động ổn định cho robot lặn ở độ sâu 50m và vận hành liên tục dưới nước trong thời gian dài ở hai chế độ AUV truyền thống và glider. Một số kết quả thực nghiệm thiết bị đẩy và bộ ước lượng góc nghiêng ba trục với sai số dưới 1° cũng được trình bày trong bài báo này.

Từ khoá: Thiết bị lặn không người lái, phương pháp phần tử hữu hạn, cơ cấu lặn nổi, thiết bị đẩy, bộ ước lượng góc nghiêng ba trục

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