THRUSTER DESIGN FOR UNMANNED UNDERWATER VEHICLES

Çetin Arda GUCER[1,+], Onur ACAR[1], Burak KANTARCIOGLU[1], Cenk ULU[1]
[1]Department of Mechatronics Engineering, Yildiz Technical University, Besiktas Istanbul Turkey
gucercetinarda@gmail.com, onuracar690@gmail.com, burakantarcioglu01@gmail.com, cenkulu@yildiz.edu.tr

Abstract

Underwater researches have been carried out for various purposes such as the protection and investigation of natural and environmental resources, various construction activities, finding and extracting fossil fuel resources, academic and industrial researches. Especially in the last two decades, unmanned underwater vehicles are effectively used in almost all of these researches. One of the most essential parts of those vehicles is their thrust system which gives them the ability to move underwater. In this study, the design of a thruster for unmanned underwater vehicles is given. The designed thruster system consists of four main parts: an electric motor, a driver circuit, a magnetic coupling transmission element, and a propeller. The electrical and mechanical designs of these parts are performed depending on the predetermined design criteria. A brushless type DC motor is chosen as an electric motor, and the required torque and rpm values are determined analytically. Depending on the chosen electric motor, a suitable driver circuit is determined. Then the propeller, the magnetic coupling element, and the motor housing are designed by using the SolidWorks software package. Pressure and fluid dynamics analyses of the housing and propeller are performed by using the Ansys software package. The thruster design is validated by simulation results.

Keywords: Unmanned underwater vehicle, thruster, magnetic coupling, transmission, propeller

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İNSANSIZ SUALTI ARAÇLARI İÇİN İTİCİ TASARIMI

Özet

Doğal ve çevresel kaynakların korunması ve araştırılması, çeşitli sualtı inşaat çalışmaları, fosil yakıt kaynaklarının saptanması ve çıkarılması, akademik araştırmalar ve endüstriyel çalışmalar gibi birçok farklı alanlarda su altı araştırmaları yapılmaktadır. Özellikle son yirmi yılda insansız sualtı araçları bu araştırmaların hemen hepsinde etkin bir şekilde kullanılmıştır. İnsansız su altı araçlarının en önemli sistemlerinden biri de onlara su altında hareket kabiliyetini sağlayan itki sistemleridir. Bu çalışma, insansız su altı araçları için bir itki sistemi tasarımı gösterilmiştir. Tasarlanan itki sistemi elektrik motoru, sürücü devresi, manyetik aktarım organı ve pervane olmak üzere dört ana bileşenden oluşmaktadır. Bu bileşenlerin elektriksel ve mekanik tasarımları önceden belirlenmiş tasarım kriterlerine göre yapılmıştır. Elektrik motoru olarak fırçasız doğru akım motoru seçilmiş ve gerekli tork ve devir sayısı değerleri analitik olarak belirlenmiştir. Belirlenen elektrik motoru için uygun bir motor sürücü devresi seçilmiştir. Pervane, manyetik aktarım elemanı ve sistem muhafazası tasarımları SolidWorks programında yapılmıştır. Sistem muhafazası ve pervanenin basınç ve akış dinamiği analizleri Ansys programı kullanılarak yapılmıştır. Geliştirilen itici tasarımı simulasyon sonuçları ile doğrulanmıştır.

Anahtar Kelimeler: İnsansız Sualtı Aracı, İtki Sistemi, Manyetik Kaplin, Güç Aktarım, Pervane

1. Introduction

Unmanned underwater vehicles (UUV) which can be autonomous (AUV) and remotely operated (ROV) are essential parts of scientific, industrial, and military work carried out in the seas [1, 2]. Through these vehicles, it has become possible to operate in depths and areas where manned underwater vehicles cannot dive due to risks [3]. Thus, with unmanned underwater vehicles, tasks like observation, research, monitoring, data collection, sample collection, search and rescue, maintenance, repair, excavation, and pipeline construction can be performed at high depths [4].

ROVs are classified into four main groups which are observation class ROVs, mid-sized ROVs, work class ROVs, and special-use ROVs [5]. Observation class ROVs can be divided into two categories as micro-class and mini-class ROVs. The depth ratings of observation class ROVs are generally less than 300 meters. Figure 1 illustrates a commercial mini-class ROV from BlueRobotics company with a 6-thruster vectored configuration. For this vehicle, 4 thrusters are used for lateral movement and 2 thrusters are used for vertical movement.

Figure 1. BlueROV2 by BlueRobotics (Source: www.bluerobotics.com)

One of the main systems of those vehicles is the thruster system that gives them the ability to move underwater. This system gives a significant influence on determining the overall performance of an underwater vehicle [6]. Figure 2 illustrates Tecnadyne Model 280 Thruster that is produced for mini-class ROVs and AUVs.

Figure 2. Tecnadyne Model 280 Thruster (Source: https://tecnadyne.com/thrusters)

The thruster system needs a multidisciplinary design process. In the design phase of this complex system, the following certain design criteria must be considered;

- Size and weight,
- Leak proofing,
- Working depth,
- Thrust force,

- Hydrodynamic structure,
- Power consumption,
- Ease of maintenance

There are not many studies on thruster design in literature. In [6], a thruster is designed and tested for specially designed Shrimp ROV. In [7], the design of a low-cost thruster for AUVs is given. In the design, a brushless DC motor is used by considering efficiency. In [8], the reverse engineering method is used in thruster design. Additionally, multi-objective evolutionary algorithm is preferred for hydrodynamics performance optimization. In [9], a hubless rim-driven thruster for ROVs is designed and developed. Specially designed brushless permanent magnet DC motor with 16 poles is used for the thruster.

In this study, the thruster design for micro and mini-class unmanned underwater vehicles is presented by considering the above-mentioned design criteria. The thrust system consists of four main subsystems. These are an electric motor, a driver circuit, a magnetic coupling transmission element, and a propeller. The electrical and mechanical designs of the thruster are performed. Then the simulation studies are done in order to validate the system design. Additionally, the rpm-thrust curve of the designed thruster is drawn. This curve shows that the desired thrust value can be provided by the designed thruster.

2. System Design

2.1. Technical Specifications

The determined technical specifications are as follows.

- The thrust system must generate a thrust force between 6kgF-7kgF.
- The nominal power of the thrust system must be between 100W-150 W.
- It should be able to operate in depth conditions up to 100 meters [10].
- It must be operable under temperature conditions from 4 ° C to 30 ° C.
- The total weight should be <1,2 kg. (Based on average market expectation)
- The total length should be <280 mm. (Based on average market expectation)
- The system should be resistant to the risk of abrasion and corrosion caused by seawater.

- There should be a nozzle to protect the propeller against substances that are under the sea and may prevent the propeller from working.

2.2. System Architecture

General system architecture for the electrical thruster consists of four subsystems which are a DC motor, a motor driver circuit, a magnetic coupling, and a propeller as shown in Figure 3.

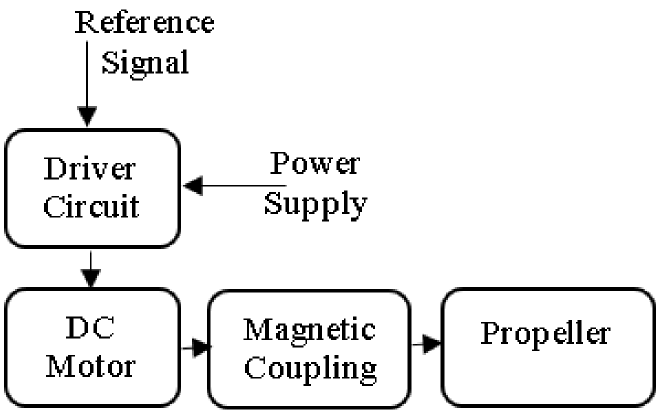

Figure 3. System Architecture

2.3 Mechanical Design

There are four main parts in the system mechanical design. These are housing, a propeller, a magnetic coupling, and a nozzle. These parts are examined in the following subsections.

2.3.1. Housing Design

Housing is the part that protects the electronic components from the water and damage. It has to overcome tough conditions underwater such as pressure, corrosion effects of salty water, and possible collisions with extraneous materials. 5083 Series Al-Mg alloy is selected due to better corrosion resistance and weight values. The front and back caps of housing are screwed into the main part. Silicone O-rings are used to provide tightness between parts. The design of the housing is given in Figure 4.

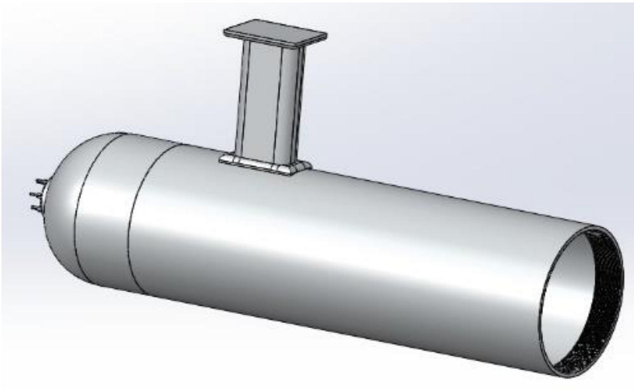

Figure 4. Housing

2.3.2. Propeller Design

Propeller is the part of the thrust system, which converts the rotation that the motor supplies to the thrust force [11]. The unique design of this propeller is done according to the criteria that the system must satisfy. Propeller mainly has 4 design parameters [12]. Those are;

- Pitch angle
- Number of blades
- Surface area
- Material

To determine the optimum parameter values of the propeller by considering design criteria, SolidWorks Flow Simulation toolbox is used. By performing simulation studies, the appropriate values of the number of blades, pitch angle, and the surface area are determined. Since the propeller material must be resistant to the corrosion effect of water and it has to be relatively light and remarkably strong, 5083 Series Al-Mg alloy is chosen for the propeller material. The final design of the propeller is given in Figure 5.

2.3.3. Magnetic Coupling Design:

To protect the motor and motor driver from water, the transmission element provides water isolation between the motor and propeller. There are several methods to isolate motor shaft (and also electrical components) from water conditions such as the use of sealing materials placed around a shaft or magnetic coupling method. In this study, the magnetic coupling method is used for power transmission. As shown in Figure 6, the magnetic coupling consists of five parts: a driver coupling, a driven coupling, a containment shroud, a shaft bearing, and a propeller shaft. The driver coupling is the mechanism that is connected to the motor.

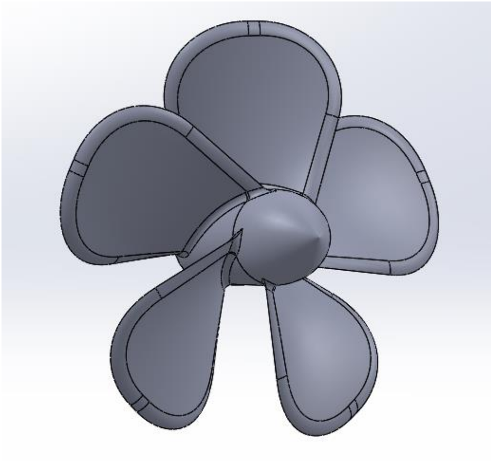

Figure 5. Propeller

Through magnetic interaction, the driven coupling reacts to the motion of the driver, resulting in a contactless transmission of mechanical energy [13]. It reduces the wear of materials and efficiency losses caused by friction due to its no-contact working principle. Nickel plated NdFeB magnets are used in the design because of providing relatively stronger magnetic forces.

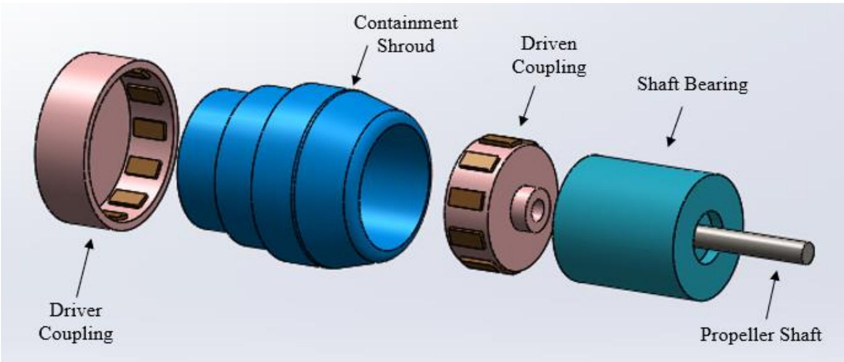

Figure 6. Magnetic Coupling

2.3.4. Nozzle Design

Nozzle reduces the vortex effects of the propeller and increases the efficiency of the propeller. Additionally, it protects the propeller from collisions and reduces environmental damage caused by the propeller. The nozzle design is shown in Figure 7.

2.4. Electrical Components

The choice of the motor has great importance in the thruster design. The motor must comply with certain design limits and must provide desired torque values in desired angular speed ranges. Mostly, two motor types are used for thrusters. Those are the brushless DC motor and the induction motor.

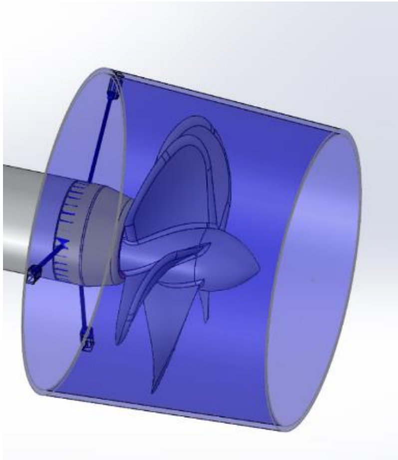

Figure 7. Nozzle Design

A brushless DC motor and a proper drive circuit are used for this study. Brushless DC motors are widely used for the thrusters of the micro and mini-class unmanned underwater vehicles. Because the power supply to be provided by the operator is DC in general. In addition, brushless DC motors can be driven relatively easily using a PWM signal via a driver circuit [14]. The determined motor has power enough to meet the desired angular velocity-torque values and it is in accordance with the length and diameter parameters reserved for the motor in the body design [15].

2.5 Final Design

The final design of the thruster is shown in Figure 8. The exploded view of the design is given in Figure 9.

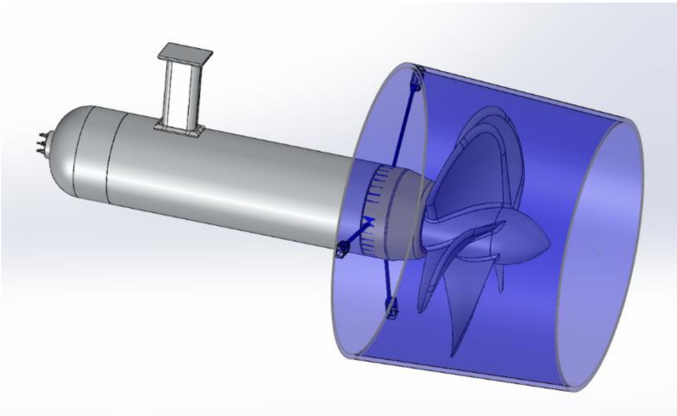

Figure 8. Assembled View

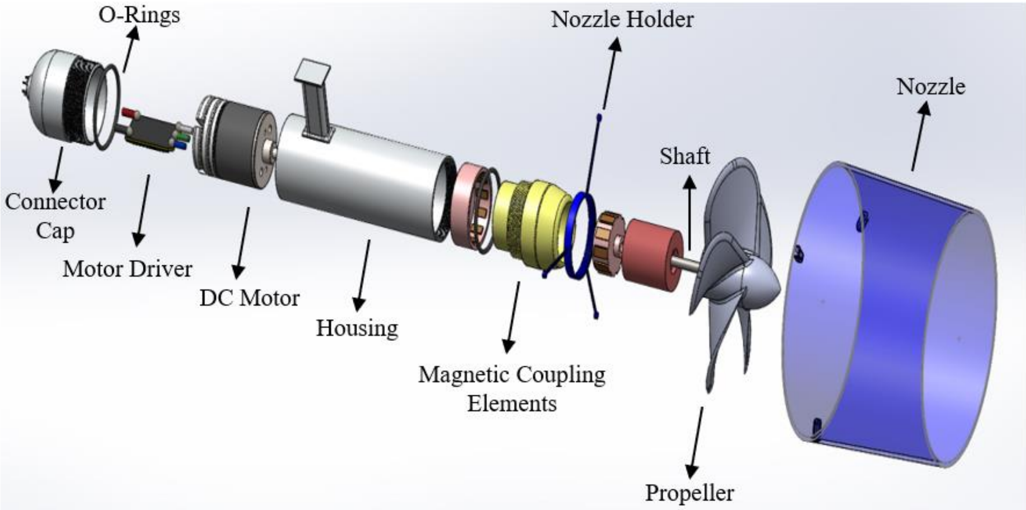

Figure 9. Exploded View

3. Simulations

Pressure analyses made on ANSYS program are shown in Figure 10 and Figure 11. The total deformation that occurs at 145 psi, which is the water pressure at 100 m depth, applied to the body when the fixing point is chosen as the top of the mounting tower is shown in Figure 10 and Figure 11.

There is almost no deformation at the ends due to the brushless DC motor located at one end of the housing and the driver part of the magnetic transmission element at the other end. The part shown as red in the middle-low section is the most deformed place. But this area has still really small value as deformation and therefore negligible. Housing is safe and operable at the conditions needed.

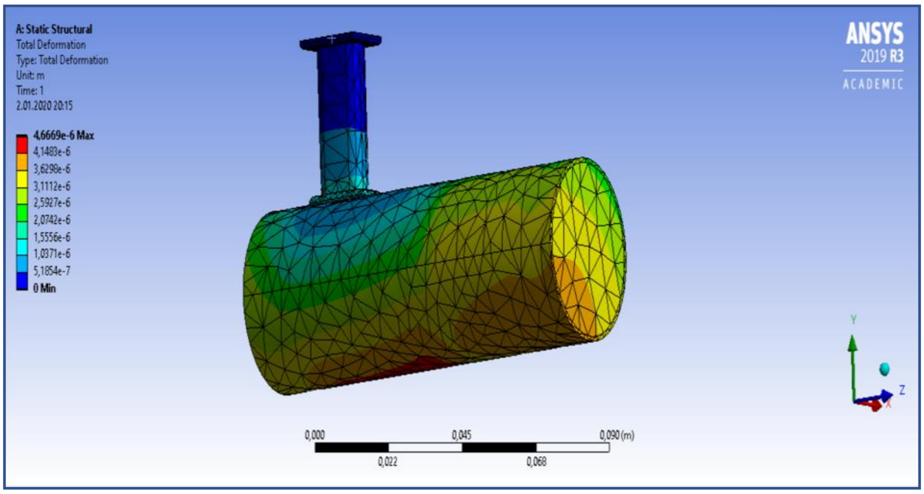

Figure 10. Deformation Analyses

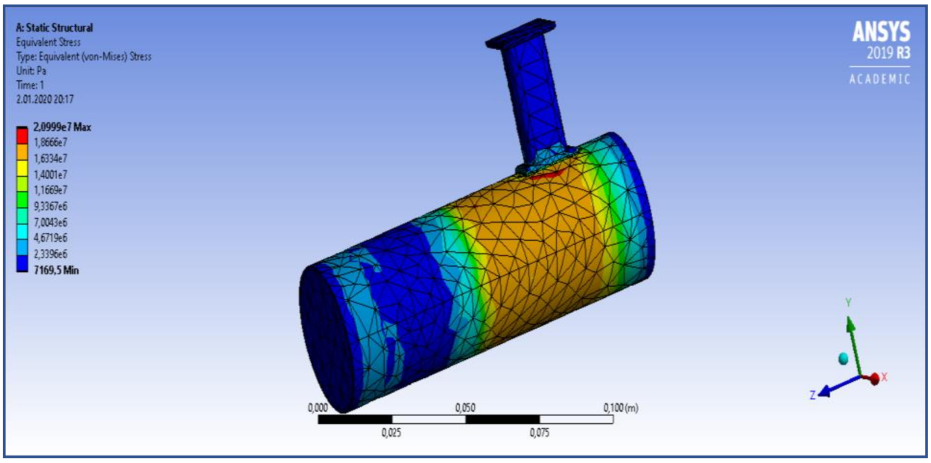

Figure 11. Stress Analyses

Likewise, in Figure 10 and Figure 11, the pressure-based equivalent stress and stress distributions made on the ANSYS program can be seen. As mentioned in the deformation analysis, the stress is concentrated in the middle parts due to the presence of the motor in one end and the drive part of the magnetic transfer element in the other end.

If the pressure in the region where the orange is concentrated is read according to the scale on the left and converted to MPa, it is calculated as 18MPa.

In Table 1, the mechanical properties of aluminum 6061 alloys that we plan to use in the implementation of the thruster are shown [16]. We can read from the table that the yield stress of this alloy starts from a minimum value of 145 MPa.

As a result of analyses, it has been shown that our system housing can withstand more than 5 times the pressure at 100m, which is the maximum working depth we have specified in our technical requirements.

Table 1. Aluminium 6061 Specifications

Property	**Aluminium 6061-T4**
Tensile Strength (MPa)	241
Yield Strength (MPa)	145
Modulus of Elasticity (GPa)	68.9

The fluid analyses, shown in Figure 12, are performed by using SolidWorks Flow Simulation toolbox.

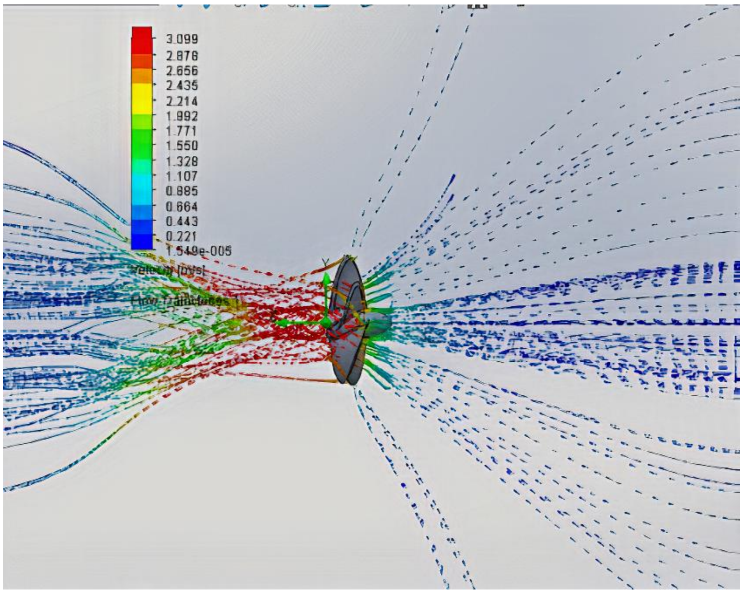

Figure 12. Fluid Analyses

Figure 13 shows the rpm-thrust curve obtained as a result of simulations run for 9 different rpm values (400 rpm, 600 rpm, 800 rpm, 1000 rpm, 1200 rpm, 1400 rpm, 1600 rpm, 1800 rpm, 2000 rpm). As it is seen from the figure, desired thrust values are provided by the designed thruster.

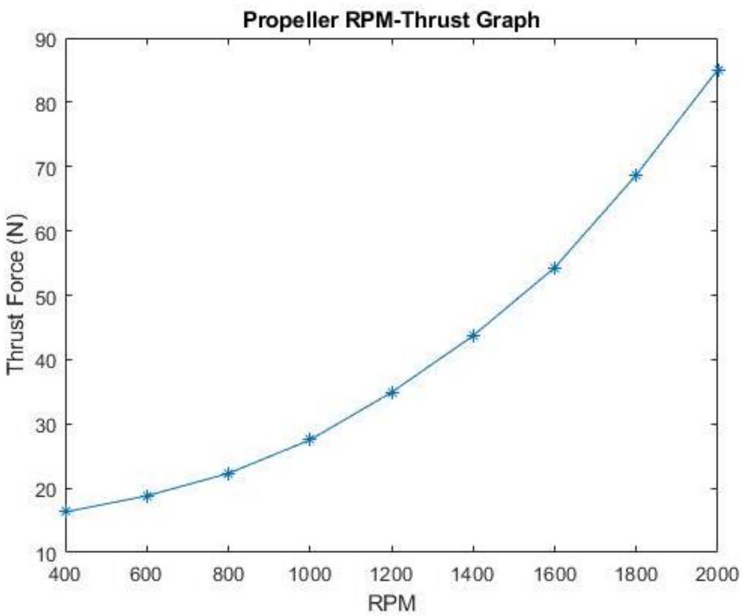

Figure 13. RPM-Thrust Graph

4. Conclusion

In this study, the thruster design for micro and mini underwater vehicles is presented. The electrical and mechanical designs of the thruster are performed depending on the predetermined design criteria. Design is validated by the simulation results and it is shown that the designed thruster provides the desired thrust value. The designed thruster can easily be produced and integrated into the remotely operated vehicles for their thrust systems.

In the future study, the designed thruster will be produced and experimental tests will be performed for the validation of simulation results.

References

[1] J. Heo, J. Kim, *Technology development of unmanned underwater vehicles*, Department of Industrial Engineering, Ajou University, Suwon, South Korea, 2017

[2] S. K. Jain, S. Mohammad, *A Review paper on: Autonomous underwater vehicle*, Int. Journal of Scientific and Engineering Research, Volume 6, Issue 2, 2015

[3] N. H. Tran, H. S. Choi, *Design, control and implementation of a new AUV platform with a mass shifter mechanism,* Int. J. Prec. Eng. Manuf. 16(7), pp 1599-1608, 2015

[4] C. Ulu, O. Canbak, M. U. Altunkaya, H. Taşkın, S. Yayla, *Development of the MarmaROV remotely operated underwater vehicle system*, International Artificial Intelligence and Data Processing Symposium (IDAP), pp. 1-6, 2017

[5] R.D. Christ and R.L. Wernli, *The ROV Manual* , 2nd ed., Butterworth-Heinemann, 2014.

[6] Muljowidodo, K., "*Design and testing of underwater thruster for SHRIMP ROV-ITB,"* Journal of Marine Sciences, vol. 38, pp. 338-345, 2009.

[7] Srujana Eega, Matthew A. Joordens, Mo Jamshidi, Fellow. *Design of a low cost Thruster for an Autonomous Underwater Vehicle* Autonomous Control Engineering (ACE) Center and ECE Department The University of Texas, San Antonio, TX, USA, 2009

[8] Rosid, Nurhayyan. *Product Redesign based on Reverse Engineering and Hydrodynamic Performance Optimization Using Evolutionary Algorithm of Underwater Thruster*. Jeju, South Korea, ICIUS 2018

[9] M. Hsieh et al., *"Integrated Design and Realization of a Hubless Rim-driven Thruster,"* IECON 2007 - 33rd Annual Conference of the IEEE Industrial Electronics Society, Taipei, 2007, pp. 3033-3038, IECON.2007

[10] N. H. Tran, H. S. Choi, N. D. Nyugen, *Study on design, analysis and control an underwater thruster for unmanned underwater vehicle (UUV),* Springer International Publishing AG, pp 753-764, 2018

[11] J. Q. T. Hyung, *Detailed design of a thruster solution for a small mass-market remotely operated underwater vehicle, Norwegian University of Science and Technology,* Department of Marine Technology, pp 15-45, Norway, 2016

[12] L. Pivano, T. A. Johansen, N. Smogeli, *A four quadrant thrust controller for marine propellers with loss estimation and anti-spin theory and experiments,* Norwegian University of Science and Technology, pp 1-15, 2009

[13] M. Shunqi, Z. Zhiming, X. Renbin, *Methods for calculating the transmission torque of magnetic transmission torque of magnetic transmission mechnanism,* International Federation for Information Processing (IFIP), pp. 631-636, Volume 207, 2006

[14] P. P. Muresan, A. Forrai, K. A. Biro, *Mathematical modelling and control of brushless dc drives – unified approach,* Technical University of Cluj-Napoca Department of Electrical Machines, Cluj-Napoca, Romania, pp 557-562, 1998

[15] B. Das, S. Chakraborty, P. Kasari, *Speed control of bldc motor using soft computing technique and its stability analysis,* International Journal of Electronics Communication and Computer Engineering, Volume 3, Issue 5, pp 1257-1262, 2012

[16] 6061 Aluminum: Get to Know its Properties and Uses, by Gabrian [Online]. Available: https://www.gabrian.com/6061-aluminum-properties/