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Initial Development of A Low-Cost and Efficient Closed-System Buoyancy Engine of A Hybrid AUV Model

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Abstract— The design of a Hybrid Autonomous Underwater Vehicle (HAUV) has been known to accommodate the efficiency of a sea glider and the maneuverability of an Autonomous Underwater Vehicle (AUV). The HAUV might have a greater capability to extend the range of underwater missions such as Intelligence, Surveillance, and Reconnaissance (ISR). One of the important parts of the HAUV is the buoyancy engine system. This study investigated a low-cost and effective model of a buoyancy engine system. The model consists of the storage of working fluids in a dry environment and an immersed model of a HAUV with float within the body of the vehicle model. This study uses three types of working fluids: air, vegetable oil, and water. The performance of the buoyancy engine systems was evaluated by injecting the working fluid into the float within the body. This study indicated that the buoyancy engine system with a float and oil has better buoyancy performance and buoyancy response compared to air and water. The buoyancy engine system with a float and oil can work with a volume fraction of the fluid 25% smaller than that of water, and 40% smaller than that of air. Since the amount of volume transferred is related to energy use by the driving motor, the results indicate that a system with oil can have higher level of energy use efficiency compared to the other two working fluids. This study shows the potential of a buoyancy engine system with a float and oil to be further developed in an efficient HAUV vehicle.

Keywords— hybrid, AUV; buoyancy, engine, low-cost, efficient.

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I. Introduction

THE world is in the era of Industrial Revolution 4.0. One of the characteristics of Industrial Revolution 4.0 is the development of intelligent and autonomous systems [1]. In the maritime sector, the use of intelligent and autonomous systems has a fairly high level of urgency. These systems could be identified in the form of conceptual architecture of the network management system on the Internet of Underwater Things (IoUT) concept [2][3]. The IoUT supports data connectivity and communication between underwater objects so that the implementation of an operation can be carried out more effectively and efficiently. One of the key components of the IoUT is the Autonomous Underwater Vehicle (AUV). The main function of the AUV is to collect and distribute the necessary underwater condition data such as temperature, pH, biochemical composition, conductivity, temperature, and depth. These data are very important for observing the potential of an underwater area. Although, data collection for underwater areas is still a sensitive issue and can have geopolitical implications.

A sea glider is one type of Unmanned Underwater Vehicle (UUV). This vehicle has the advantage of a high level of energy use efficiency. This makes the sea glider able to operate for data collection in underwater areas for a long period. The Sea glider vehicle with a hydrodynamic design and a pressurized hull could be used on missions for a full year [13]. Unlike the common AUV with a thruster system and high maneuverability, sea gliders rely on buoyancy only to move vertically at sea depths. Therefore, there is a demand for a UUV with high efficiency and maneuverability characteristics in the form of a Hybrid Autonomous Underwater Vehicle (HAUV) [4][6][7][8].

To be able to move vertically at depth, HAUV uses a buoyancy engine mechanism. The buoyancy engine mechanism was first developed on the *Slocum* underwater glider [9]. With this mechanism, the *Slocum* can move vertically with a gliding angle of about 35° and a speed of 0.5 *knots*. Another type of buoyancy engine system known as the Leduc Ballast system is used in the *ALACE* buoy [10]. This buoy system uses a plunger piston that moves in and out at the bottom of the float to change the buoyancy of the vehicle. In the development of further glider vehicles, such as the *Slocum Battery* and *Slocum Thermal* [11] and Spray [12], the buoyancy engine mechanism has used battery power as well as utilizing a pressurized hull. Research in [13] and [14] shows the development of a Hybrid AUV with a special buoyancy engine mechanism. The developed buoyancy engine system uses a hydraulic pump which is rotated by a brushless DC motor to transfer oil fluid from the internal bag to the external bag. The main parts of the system include internal and external pockets, pump and battery system, dry box, and buoy.

Despite the various studies of buoyancy engines, discussion on the effectiveness of working fluids in a simple and economical system is relatively rare. This research developed a low-cost and effective model of a closed-system buoyancy

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engine for a HAUV model. The buoyancy engine system was a closed system with the working fluid injected into a flexible internal bag as a bladder in the vehicle body. One of the advantages of this closed system is its potential for use at high pressure in deep-sea areas. A preprogrammed microcontroller regulated the volume transfer mechanism of the working fluid. The simple mechanism of the system supports the low production cost. The buoyancy performance was evaluated in the water tank environment. This research could be an important preliminary step in developing efficient and economic operational HAUV.

II. Experimental Setup

The experimental evaluation of the buoyancy engine performance was performed in custom-built water tank equipment. The tank mainly has a rectangular cross-section with a chamfered on the left and right sides. The tank's dimension is 0.6 m in length, 0.35 m in width, and 0.5 m in height. Hence, the tank has a full water volume capacity of 0.105 m^3 or 105 ℓ. The buoyancy engine system consists of working fluid storage and a vehicle model with a flexible buoy. The storage consists of two 60-mℓ syringes, while the vehicle body is a simple tubular plastic jar with a rubber balloon as a flexible buoy inside the body. The vehicle model has a diameter of 0.07 m and a height of 0.14 m. The working fluid storage was placed in a dry environment while the vehicle model and bladder systems were immersed in the water tank. These two systems were connected through a plastic hose.

Figure 1 shows the fluid transfer system of the developed buoyancy engine model. As shown in the figure, the working fluid storage in the syringes is fixed in the bottom part of the system. The push and pull translation motion of the plunger of the syringe is activated by the rotation motion of the lead screw T8 at the upper side. A servomotor of MG996 governs the rotational speed of the lead screw motion. A flexible coupling is placed between the servomotor and the lead screw to create an allowance for minor misalignment. In the figure, the servomotor is connected to an electrical circuit with a microcontroller. The program in the microcontroller determines the duration of the shaft rotation, which is related to the translation length and repetition of the push and pull motion. The systems were powered by two batteries of BL-5C (each with 950 mAh and 3.7 V) at the bottom of the platform.

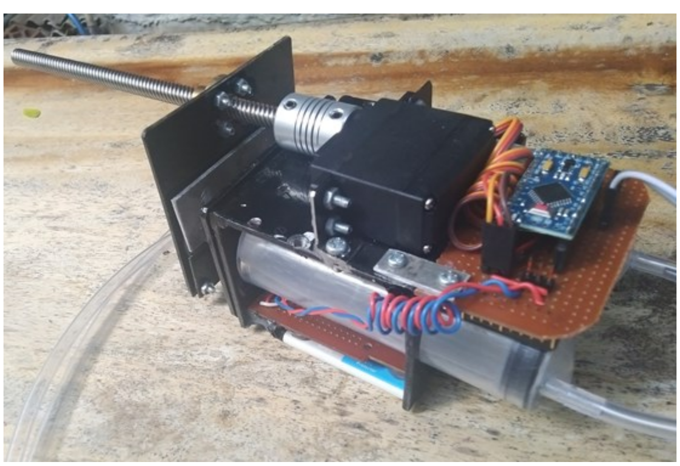


Figure 1 Fluid transfer systems.

The working fluids in this study were divided based on the Specific Gravity (*SG*) of the fluids. *SG* can be expressed as the ratio of the density of the working fluid to the density of water. This study considered three working fluids: air ($SG = 0.00103$), vegetable oil ($SG = 0.926$), and water ($SG = 1.000$). There were three configurations that needs to be investigated: Buoy-Air, Buoy-Oil, and No buoy-Water. These configurations should be useful to observe the effects of working fluid on the buoyancy performance of the developed buoyancy engine model.

The HAUV model will float (positive buoyancy) and sink (negative buoyancy) due to a change in the volume of working fluid in the buoyancy engine system. The measurement aspects of this study were focused on the rate of change of the flow in the system and the rate of change of the depth. The duration of the changes was counted manually by using a stopwatch. Buoyancy engine performance was divided into buoyancy time and buoyancy response by considering fluid volume fraction R_v, floating time ratio R_{tp}, and sinking time ratio R_{tn}. The fluid volume fraction R_v is the ratio of the transferred fluid volume, V_f, to the maximum capacity of the fluid, V_{fmax}, which can be written as

$$R_v = \frac{V_f}{V_{f\,\max}} \quad \textbf{(1)}$$

The floating duration ratio R_{tp} and the sinking duration ratio R_{tn} are the ratios between the duration of the floating and sinking motion of the HAUV model, t_m, to the duration of the servo motor motion, t_s, and can be expressed as

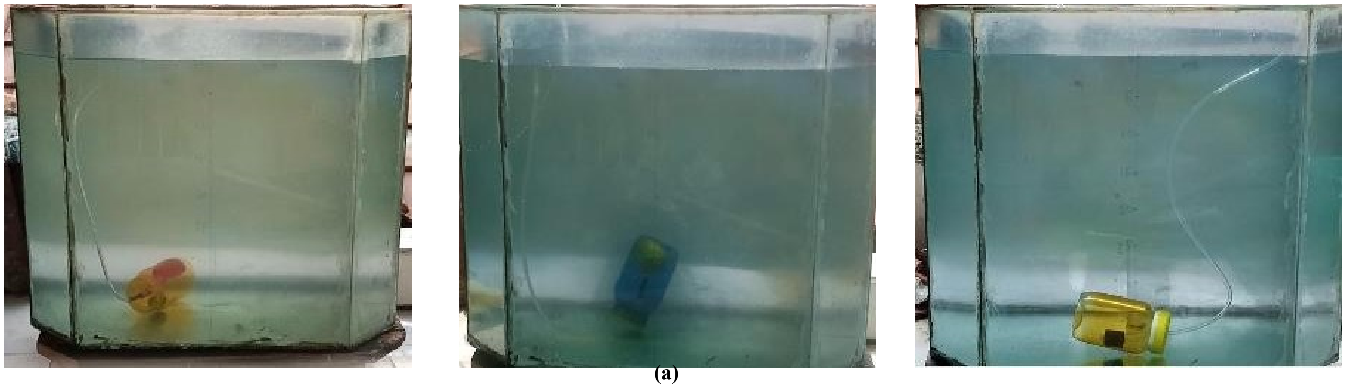
$$R_{tp} = R_{tn} = \frac{t_m}{t_s} \quad \textbf{(2)}$$

Each measurement in the experimental scheme was repeated five times to obtain the average value and standard deviation of the results.

III. Results and Discussion

Figure 2 shows the buoyancy states of the submerged vehicle model for each type of working fluid. On the top row of the figure, the developed buoyancy engine model could provide a sufficient negative buoyancy force to sink the vehicle model. The buoyancy engine model could also provide a sufficient positive buoyancy force to float the vehicle model, as can be seen on the bottom row of the figure. The ability to change the buoyancy state indicates the reliability of the overall systems.

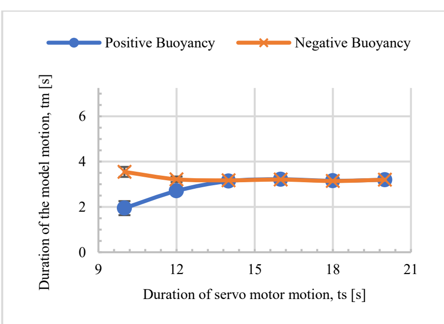
Figure 3 shows the results of the response time measurement of the vehicle model. The plots on the figure relate the duration of servo motor motion, t_s, and the duration of the vehicle model motion, t_m. The figure also depicts positive buoyancy and negative buoyancy states for floating and sinking, respectively. The higher values of t_s indicate the more volume of the working fluid displaced by the system. On the other hand, the higher values of t_m show the slower response of the vehicle to sinking or floating. The result indicates that different configurations of the working fluid affect the performance of the buoyancy engine system. The vertical symmetrical lines at each measurement value are the standard deviation of the measurements.



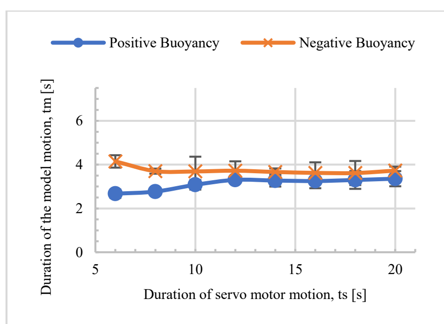
(a)

(b)

Figure 2 Buoyancy states of the submerged model (a) Sinking state, (b) Floating state (Left: Buoy-Air, Middle: Buoy-Oil, Right: No Buoy-Water)



(a)



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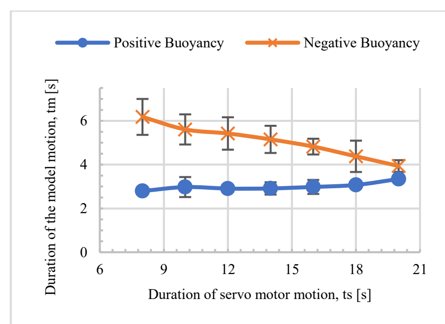
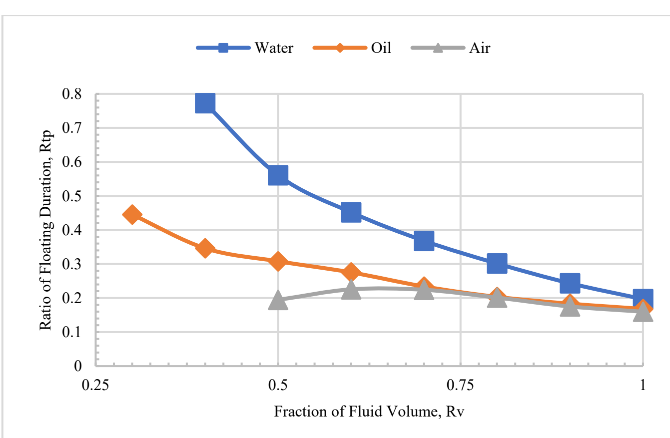
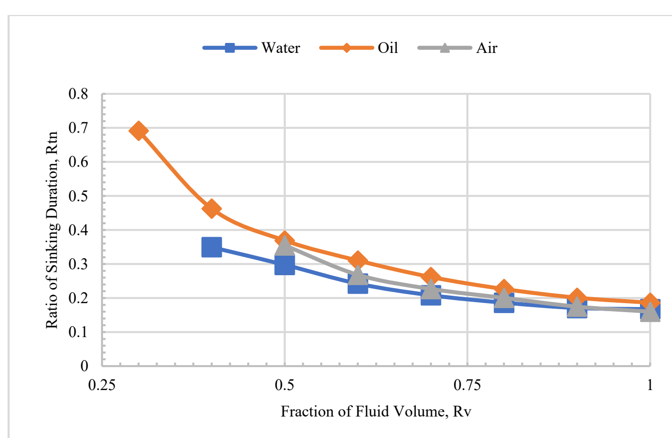


(c)

Figure 3 Response time of the vehicle model: (a) Buoy-Air, (b) Buoy-Oil, (c) No Buoy-Water.



(a)



(b)

Figure 4 Response performance of the buoyancy engine model: (a) Positive buoyancy (b) Negative buoyancy.

Figure 3(a) shows the results of the response time of the Buoy-Air configuration. The response of the vehicle model to positive and negative buoyancy tends to be constant if the servo motion time t_s is greater than 14 *s*. However, when the value of t_s is less than 14 *s*, there is a significant time lag between sinking and floating. This time lag indicates that the vehicle model takes a slower time to sink but is faster to float. The vehicle model with Buoy-Air configuration has no response to the changes in the working fluid volume when the servo motion is less than 10 *s*. Hence, the buoyancy engine system with a float and working fluid of air has a critical transferred volume to function properly and symmetrically between sinking and floating responses. Furthermore, the result indicates that to change the buoyancy state of this configuration, the system requires a relatively large fluid volume change.

Figure 3(b) shows the response time of the Buoy-Oil configuration. In the figure, the response time of the vehicle model to positive and negative buoyancy is relatively constant for a longer range of t_s. Furthermore, the results indicate a consistent time lag between the duration of sinking and floating. The time lag shows that the floating response of this configuration is faster than the sinking response. The fluid residue in the buoy, due to a reduction in suction performance of the syringe by the vegetable oil, might cause this time lag. The lower minimum value of t_s of this configuration could be advantageous in generating buoyancy force by small volume change.

Figure 3(c) shows the response time of the No Buoy-Water configuration. As shown in the figure, this configuration has a significant difference in response to positive and negative buoyancy forces. The response to positive buoyancy is relatively constant compared to the negative slope of the negative buoyancy. Further, the negative slope indicates a higher sinking response at increasing volume changes. This configuration is not suitable for an underwater vehicle with the requirement of fast buoyancy response, but advantageous for a high-precision underwater measurement or sampling that requires a slowly sinking vehicle. This configuration has a similar range of t_s to the Buoy-Oil configuration, indicating a responsive system to relatively small changes in fluid volume.

Figure 4 shows the performance of positive and negative buoyancy responses of the developed buoyancy engine model. The response performance to the presence of positive buoyancy force is depicted in Figure 4(a). Dominantly, at higher values of R_v, there is a negative slope relationship between the value R_v and R_{tm}. Most of the developed configuration has a faster response in floating than sinking. There is a non-linear relationship between the duration of response to the change in volume of the working fluid. The working fluids of oil and air have a relatively similar trend of response performance at R_v higher than 0.7. Buoyancy engines with water have a lower floating response performance than air and oil. At the values of R_v = 0.7, there is a 40% decrease in floating response performance of buoyancy engine with working fluid of water. The shape of the performance curve in the working fluid of air indicates that there is a maximum value of R_{tp}. This maximum value is the lowest response performance and can be related to the critical volume of the Buoy-Air as shown in Figure 3(a).

Figure 4(b) shows the negative buoyancy response performance of the developed buoyancy engine systems. Either higher value of R_v or lower sinking time ratio R_{tn} indicates a faster sinking response of the vehicle model. Similar to the results of positive buoyancy response, the sinking response time is not linearly proportional to the change in volume of the working fluid. As can be seen in Figure 4(b), the trends of the response performance of the developed buoyancy engine systems to the negative buoyancy are not significantly different. At R_v = 0.6, the sinking response performance of the working fluid of air is about 15% faster than the oil and about 11% slower than the water. Hence, the working fluid of oil tends to be slower in responding to negative buoyancy forces. However, as depicted in Figure 4(b), the working fluid of oil has a higher sensitivity to negative buoyancy in a smaller volume fraction compared to working fluids of air and water.

A buoyancy engine system with a working fluid of oil should have advantages over air and water. This result is consistent with the selection of working fluid for the buoyancy engine system in [14]. In terms of response, the oil is still capable of responding to positive and negative buoyancy forces at small volume changes. The Buoy-Oil configuration responds to the buoyancy force with a volume fraction of the fluid 25% smaller than that of water and 40% smaller than that of air. Less volume of the transferred fluid to generate positive or negative buoyancy forces means less power consumption of the buoyancy engine. Hence, this condition could be related to higher energy efficiency in the buoyancy engine system. It is also easier to control the buoyancy force in the Buoy-Oil configuration since it has a relatively small difference between the floating and sinking responses. However, since there are indications of a performance reduction due to interaction between oil and pump rubber, it is necessary to observe the suitable type of oil for a particular buoyancy engine system.

IV. Conclusion

The developed closed-system buoyancy engine could provide positive and negative buoyancy forces to control the state of the HAUV model. Working fluids affect the buoyancy response performance of the vehicle model. Performance evaluation of the closed-system buoyancy engine could be characterized by the relation between the duration of motion of servomotor and vehicle model, and the relation between fluid volume fraction and the ratio of floating or sinking duration ratio of the vehicle model. In generating buoyancy force, the Buoy-Air configuration introduces a critical value in the change of fluid volume. The No Buoy-Water configuration has a lower buoyancy response performance than other configurations. In generating buoyancy forces, the Buoy-Oil configuration has a higher sensitivity to the change in fluid volume than other configurations. The Buoy-Oil configuration in this study could be further implemented in designing an efficient closed-system buoyancy engine of a Hybrid AUV.

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References

[1] Rojko, A. (2017): Industry 4.0 Concept: Background and Overview, *International Journal ofInteractive Mobile Technologies*, Vol. 11, No. 5, doi: 10.3991/ijim.v11i5.7072.

[2] Raj, D., Lee, J., Ko, E., Shin, S.Y., Namgung, J.I, Yum, S.H., and Park, S.H. (2020): Underwater Network Management System in Internet of Underwater Things: Open Challenges, Benefits, and Feasible Solution, *Electronics*, 9, 1142, doi:10.3390/electronics9071142.

[3] Heidemann, J., Stojanovic, M., and Zorzi, M. (2012): Underwater sensor networks: applications, advances and challenges, *Phil. Trans. R. Soc. A* 370, 158–175. doi:10.1098/rsta.2011.0214

[4] Eriksen, C. C., Osse, T. J., Light, R. D., Wen, T., Lehman, T. W., Sabin, P. L., Ballard, J. W., and Chiodi, A. M. (2001): Seaglider: A long-range autonomous underwater vehiclefor oceanographic research, *IEEE Journal of Oceanic Engineering,* 26(4), 424–436, https://doi.org/10.1109/48.972073.

[5] Li, B. and Su, T.C. (2017): Heading Autopilot of Autonomous Underwater Vehicles With Internal Moving Mass, *J. Comput. Nonlinear Dynam*., Vol. 12, No. 2. https://doi.org/10.1115/1.4034727

[6] Kartidjo, M.W., Manullang, R.A.M., Jaya, A.S. (2019): Hydrodynamic design and analysis of low-drag Hybrid-AUV ITB, *Proceedings of 15th International Conference on Intelligent Unmanned Systems*. (ISSN: 2508-4127)

[7] Latifah, A., Fatimah, D. D. S., Hakim, B. L., and Chandrahadinata, D. (2019): Depth controldesign and simulation of hybrid underwater glider. In *Journal of Physics: Conference Series* (Vol. 1402). Institute of Physics Publishing. https://doi.org/10.1088/1742- 6596/1402/4/044018

[8] Tran, N. H., Huynh, T. D., Ton, T. P., and Huynh, T. H. (2021): Design of depth control for hybrid auv. In *Lecture Notes in Electrical Engineering* (Vol. 685 LNEE, pp. 521–531). Springer. https://doi.org/10.1007/978-3-030-53021-1_53

[9] Stommel, H. (1989): The Slocum Mission, *Oceanography*, 2(1), 22–25, https://doi.org/10.5670/oceanog.1989.26.

[10] D'Asaro, E. A. (2003): Performance of Autonomous Lagrangian Floats, *Journal of Atmospheric and Oceanic Technology*, Vol. 20, No. 6, 896–911, https://doi.org/10.1175/1520-0426(2003)020%3C0896:POALF%3E2.0.CO;2.

[11] Webb, D. C., Simonetti, P. J., and Jones, C. P. (2001): SLOCUM: An underwater glider propelled by environmental energy, *IEEE Journal of Oceanic Engineering*, 26(4), 447–452, https://doi.org/10.1109/48.972077.

[12] Sherman, J., Davis, R. E., Owens, W. B., and Valdes, J. (2001): The autonomous underwater glider "Spray," *IEEE Journal of Oceanic Engineering*, 26(4), 437–446, https://doi.org/10.1109/48.972076.

[13] Kartidjo, M.W., Nugroho S.A., Prayogo N. (2013): Design and Operation Analysis of Hybrid AUV. In: Nonami K., Kartidjo M.W., Yoon KJ., Budiyono A. (eds) Autonomous Control Systems and Vehicles. Intelligent Systems, Control and Automation: Science and Engineering, Vol. 65, Springer, Tokyo. https://doi.org/10.1007/978-4-431-54276-6_18

[14] Hanafi, A.F. (2013): Perancangan, pembuatan dan pengujian *buoyancy engine* Hybrid AUV ITB. Tugas Akhir Sarjana, Institut Teknologi Bandung.