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Proposed Mathematical Modeling of Small Remotely Operated Vehicle (ROV) Movement

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Abstract. In designing of Remotely Operated Vehicle (ROV), the most important issue is how to formulate the movements of the vehicle. This paper proposes the mathematical model of ROV movement. Combination of statics disciplines and dynamics of ROV movement are needed to formulate the mathematical model of ROV. Statics refers to the forces and moments that work on the physical system around the equilibrium point, dynamics refers to the effect of force on the movement of the object. Linear mathematical models analyzed can be combined or separated by taking into account the circumstances surrounding environment such as velocity vector of the linear state of the vehicle body (surge, sway and up) and angular (roll, yaw and pitch). Simulation results show that the movement of vehicles, both basic and combined movements have reliable characteristics.

Keywords: Mathematical, model, movement, ROV

1. Introduction

Underwater-sensing vehicles namely ROV and AUV have been applied in various submarine fields. In line with its development, the vehicle tends to be used as an autonomous small underwater vehicle, both moored in rivers, lakes and oceans. Underwater sensing vehicles are commonly referred to as underwater vehicles. ROV and AUV are useful in various fields and for various applications such as inspection, mapping or bathymetry [1].

Research on underwater sensing vehicles allows humans to investigate deep and dangerous underwater environments without entering the environment. The ongoing development of the vehicle is more directed to the vehicle for ROV, especially in the control system. The development of effective controls for ROV is not easy because of the nonlinear characteristic of the vehicle and disturbances from the external environment such as water currents, waves, temperature and pressure changes [2], [3].

A number of studies regarding the development of effective control algorithms for ROVs have been carried out by [1], [4]–[6]. One of them is that the feedback signal quality of the ROV sensor system plays an important role in vehicle performance since the signal, influenced by sound, can make lower quality of ROV control and even cause system instability. Thus, the need to develop effective orientation observers for ROVs to provide accurate and strong signals needs to be improved [3], [7].

Further development, Dukan and Sørensen [8], [9] made automating on ROV so that ROV was not only a movement control function, but also improved positioning accuracy and left the pilot to oversee ROV operations. This is a development carried out by [10]. Development occurs in the dynamic position (DP) of the ROV system. A further improvement in the DP system is including automatic control functions for altitude and terrain control. During the survey operation for seabed mapping and monitoring in various fields the function is needed.

Beside the development of the control system, there are several studies that apply underwater vehicles as a sensing system. Adh Khadhraoui et al. [2] studied the ROV as an ultraportable submarine vehicle expected for observation and exploration of underwater historical sites. ROV is equipped with two cameras for tele-exploration. In order to stabilize the ROV, the system must be stabilized for the desired position and attitude under the hydrodynamic effect. Based on the ROV kino-dynamic model proves that required condition is unsatisfactory, so there must be continuous linear feedback to solve stability problems. Therefore, the homogeneous control of the time series must be described explicitly [2], [11] . Some other application examples of using this vehicle can be found in [6], [12]–[14] . This paper proposes the mathematical model of ROV movement. Combination of statics disciplines and dynamics of ROV movement are needed to formulate the mathematical model of ROV. Statics refers to the forces and moments that work on the physical system around the equilibrium point, dynamics refers to the effect of force on the movement of the object.

2. Dimensional Vehicle Movement Model

The most important thing in designing this underwater vehicle is how to formulate the movement of the vehicle. Figure 1 shows a picture of the design and position of the vehicle on the coordinate plane. Based on these coordinates, there are 6 (six) degrees of freedom (DOF), where the vehicle can move as follows: forward, surge sideways (sway) and float up (up) in the direction of the axis X, Y and Z and roll, go up and turn (yaw) following the X, Y and Z axis.

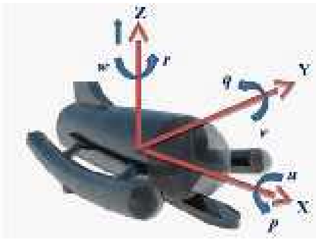


Figure 1. Underwater Vehicle Movement Design

The vehicle weight is assumed that capable of making the entire vehicle sink, so control will be prioritized to handle the downward force (buoyancy). The center of gravity is in the middle of the vehicle's body, so this will create a robotic stability during pitch and roll movements. Vehicle movement depends entirely on the movement of 4 (four) DC motors. The four motors are 2 (two) motors X1 and X2, which are located with X axis; a main motor that located between X1 and X2 and another motor that located in Z axis.

Motor X1 and X2 are used to provide force along the X axis and torque on the Z axis. The resultant force of the two motors is responsible for the surge movement of the vehicle, while the resultant torque is responsible for the turning motion. From the movement of the 4 motors, it can be stated that the vehicle has 4 degrees of freedom, by eliminating sway and roll movements. In other words, this vehicle acts as a non-holonomic vehicle. Other movements can be done by arranging a combination of the four basic movements above.

The classic goal of vehicle design is that the vehicle can maneuver well in certain areas. Some tests are usually carried out to investigate the performance of the vehicle. Therefore, some researchers are working to build a mathematical model of vehicle movement and its environment.

Based on the above design, the vehicle model can be derived by looking at the vehicle as a point in the 3 dimensional plane of cartesius coordinates with global coordinates {X, Y, Z}. The vehicle has 5 (five) position parameters represented as pc = {xc, yc, zc,   c,   c}, where (xc, yc, zc) is the spatial position of the vehicle in the global coordinate system and (c,   c) are respectively each vehicle's direction angle to the X axis and Z axis. This principle is shown in Figure 2 below.

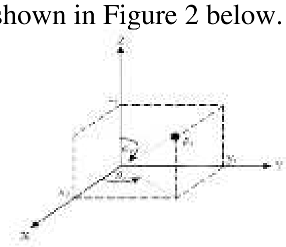


Figure 2. Vehicle workspace in X,Y,Z plane

The important thing to note in this vehicle movement model as previously explained is the 4 degrees of freedom of motion as shown in Figure 2. Thus the vehicle can be modeled by observing dynamic parameters nonlinearly, coupled, time-varying, and uncertainty. [15] model the parameters as follows.

$$M_R X_b + C(X_b)X_b + D(X_b)X_b + g(X_E) = F + F_d \tag{1}$$

$$F = [X\ Y\ Z\ K\ M\ N]^T \tag{2}$$

$$X_b = [u\ v\ w\ p\ q\ r]^T \tag{3}$$

where

M_R *is* matrix of vehicle body mass movement and water mass;
C is matrix of centripetal force and *Coriolis*;
D is matrix of *hydrodynamic dumping*;
G is matrix force and inertia moment.

The body frame of the vehicle moves and always has a normal position at the center of gravity. From equations (1), (2) and (3), Xb is the velocity vector of the linear state of the vehicle body (surge, sway and up) and angular (roll, yaw and pitch) as shown in Figure 2. F is a force vector and torque produced by the degree of freedom of motion and Fd are vectors that represent environmental disturbances. Other parameters are MR, C (Xb), D (Xb) and g (XE) defined as follows,

$$M_R = d \begin{bmatrix} m - X_u \\ m - Y_v \\ m - Z_w \\ I_x \ - K_p \\ I_y \ - M_q \\ I_z \ - N_r \end{bmatrix} \tag{4}$$

$$C(X_b) = \begin{bmatrix} & 0 \quad 0 \quad 0 & 0 & (m - Z_w)w & (Y_v - m)v & \\ & 0 \quad 0 \quad 0 & (Z_w - m)w & 0 & (m - X_u)u & \\ & 0 \quad 0 \quad 0 & (m - Y_v)v & (X_u - m)u & 0 & \\ 0 & (m - Z_w)w & (Y_v - m)v & 0 & (m - X_u)u & (M_q - I_y)q \\ (Z_w - m)w & 0 & (m - X_u)u & (N_r - I_z)r & 0 & (I_y - M_q)q \\ (m - Y_v)v & (X_u - m)u & 0 & (I_y - M_q)q & (K_p - I_x)p & 0 \end{bmatrix} \tag{5}$$

$$X \ (E) = \begin{bmatrix} 0 \\ 0 \\ 0 \\ -(y_G - y_B)c \quad + (z_G - z_B)c \\ (z_G - z_B)s \quad + (x_G - x_B)c \\ -(x_G - x_B)c \quad - (y_G - y_B)s \end{bmatrix}$$

(6)

In other conditions, vector $X_E = [x, y, z.\ \phi, \theta, \psi]$ are variable conditions; state of earth space: movement of the position of x, y and z and yaw angle, up and roll.
The relationship between the speed of the vehicle's body and the state of the earth's space can be written as follows,

$$XE = J(XE)Xb \tag{7}$$

Based on the above design, there are 2 (two) pairs of motors that will produce 2 (two) pairs of speeds, namely: the translation speed v1, and v2, and the rotational speed ω_1 dan ω_2, where v1 and ω_1 are motor speed X1 and X2 and v2 and ω_2 are motor speed Z1 and Z2.

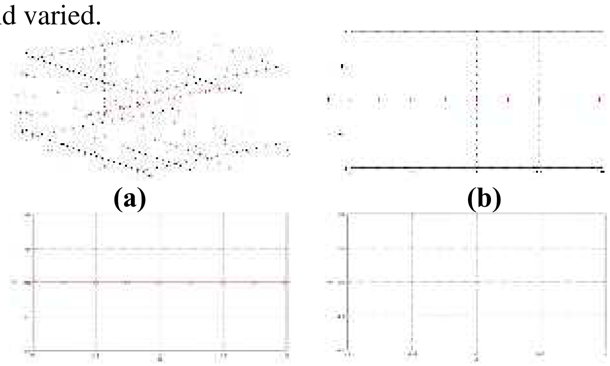
3. Results and Discussion

The initial approach to a vehicle design is actually and can be used as an illustration for the process of collecting and analyzing vehicle movement data through computer simulation. However, verification of effective vehicle performance can only be achieved by using a real vehicle. The results will be displayed are the experimental results in the form of an underwater vehicle computer simulation. The experiment is done by simulating the underwater vehicle mathematical model discussed above. Octave Version 4.0.3 software is used to simulate the above equations. The simulation results will be displayed in the form of visualization of the movement of underwater vehicles shown in figure 3 through figure 7.

At the beginning, experiments are carried out to test the basic movement of the vehicle, such as: surge, yaw, pitch and up. The initial position of the vehicle is assumed to be in the coordinates {-20, 0, 0, 0, 0}. Figure 4 shows the forward motion of the vehicle where the vehicle moves transitively, v1, in the direction of the X axis. This movement occurs by only activating the X1 and X2 motor pairs with the same speed and direction. To simplify the analysis, 3 (three) dimensions images are combined with 2 (two) dimensions per XY plane, XZ plane and YZ plane.

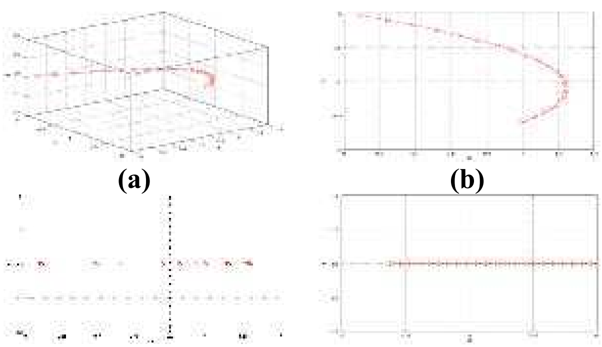
The robot movement shown in figure 4 is a yaw mode, which is the rotation of the robot that rests on the Z axis. This movement occurs by activating the X1 and X2 motors with different speeds, where the X2 motor speed is greater than X1. As a result, there is a rotation speed, ω_1, with the direction to the right.

Figure 5 and 6, each showing the movement of the vehicle when it in pitch and up mode. This is obtained by adjusting the motor speed Z1 and Z2. If both speeds are the same, you will get an upward movement with translational velocity, v2, in the direction of the Z axis. While different speeds will occur upward with a rotational speed, ω_2, with an X axis. If the two motor pairs are combined, there will be movement which is more complex and varied.



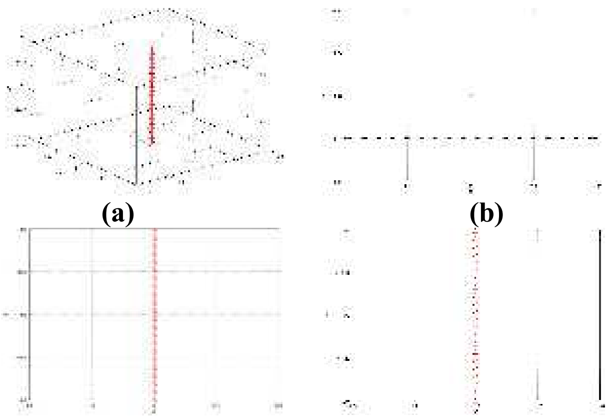
(a) **(b)** **(c)** **(d)**

Figure 3. Surge Mode (movement in x direction) Simulation Result
(a) 3D plane; (b) X to Y plane; (c) X to Z plane; (d) Y to Z plane



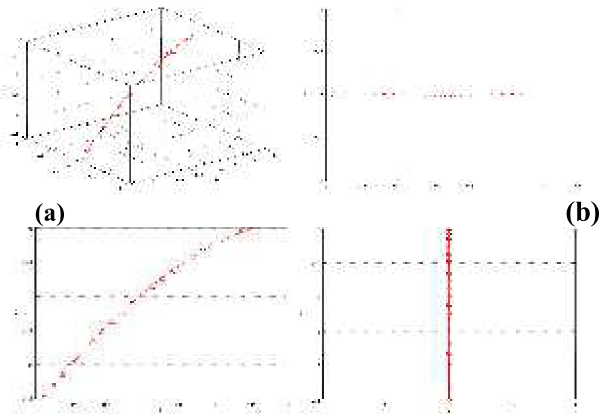
(a) **(b)** **(c)** **(d)**

Figure 4. Yaw Mode (rotation on the y axis) Simulation Result
(a) 3D plane; (b) X to Y plane; (c) X to Z plane; (d) Y to Z plane



(a) (b) (c) (d)

Figure 5. Pitch Mode (rotation on z axis) Simulation Result
(a) 3D plane; (b) X to Y plane; (c) X to Z plane; (d) Y to Z plane



(a) (b) (c) (d)

Figure 6. Up Mode (movement in z direction) Simulation Result.
(a) 3D plane; (b) X to Y plane; (c) X to Z plane; (d) Y to Z plane

Figure 7 shows the movement of a vehicle which is a combination of basic movements. At the beginning of the image, it appears that the vehicle moves up and turns at once, so the vehicle rises and rotates to the right. Then, upwards and turns direction opposite, so the vehicle moves down and rotates to the left simultaneously. In addition, the movement of the vehicle and the transition between movements appear smooth as evidence of reliable control.

From the simulation results that discussed in figures 4 - 7 above, the results of the research study show that robots can move well and cannot escape from slips. Some matters that affect the environment that is applied to the robot are assumed to be without presence of currents, waves, and other disturbances that are not like that done by [3] [16] . In addition, the communication applied is ideal and has been done manually which is not automatically carried out [17] . Weaknesses that obtained in this simulation is a robot motion control system that cannot be controlled by robot height from the robot surface. Relying, [18]–[20] suggests a dynamic position algorithm which can be applied in the future in a real environment to stabilize the ROV position that needed for compiling under the hydrodynamic effect.

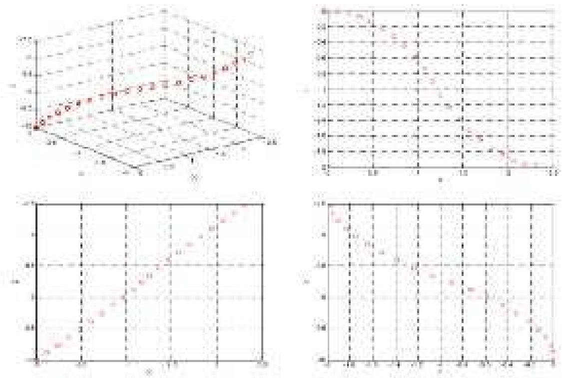


Figure 7. Combined-movement simulation results.
(a) 3D plane; (b) X to Y plane; (c) X to Z plane; (d) Y to Z plane

4. Conclusion

Characteristics of underwater vehicle include the shape, dimensions, control and movement has been derived through a mathematical model of 3-dimensional underwater vehicle movement. The simulation results show that the movement of the vehicle, both basic movements and combinations have reliable characteristics.

References

[1] A. Khadhraoui, L. Beji, S. Otmane, and A. Abichou, "Stabilizing control and human scale simulation of a submarine ROV navigation," *Ocean Eng.*, vol. 114, pp. 66–78, Mar. 2016.

[2] Adel *et al.*, "Explicit homo-genous time varying stabilizing control of a submarine ROV," in *The 10th International Conference on Informatics in Control, Automation and Robotics*, 2013, pp. 26–32.

[3] K. D. Le, H. D. Nguyen, D. Ranmuthugala, and A. Forrest, "A heading observer for ROVs under roll and pitch oscillations and acceleration disturbances using low-cost sensors," *Ocean Eng.*, vol. 110, pp. 152–162, 2015.

[4] X. Guoqing, T. Li, G. Fengshui, C. Qiang, and L. Jing, "Design of a hybrid controller for heading control of an autonomous under water vehicle," in *Proceedings of the IEEE International Conference on Industrial Technology (ICIT)*, 2009, pp. 1–5.

[5] K. D. Le, H. D. Nguyen, and D. Ranmuthugala, "Design, Modelling and Simulation of a Remotely Operated Vehicle - Part I," *J. Comput. Sci. Cybern.*, vol. 30, no. 2, pp. 106–116, 2014.

[6] M. S. M. Aras, S. S. Abdullah, M. Z. A. Rashid, A. A. Rahman, and M. A. A. Aziz, "Development and modeling of unmanned underwater remotely operated vehicle using system identification for depth control," *J. Theor. Appl. Inf. Technol.*, vol. 56, no. 1, pp. 136–145, 2013.

[7] L. Govinda, T. Salgado-Jiménez, M. Bandala-Sanchez, L. Nava-Balanzar, R. Hernandez-Alvarado, and J. Antonio, "Modelling, design and robust control of a remotely operated underwater vehicle," *Int. J. Adv. Robot. Syst.*, vol. 11, no. 1, pp. 1–16, 2014.

[8] F. Dukan and A. J. Sørensen, "Sea floor geometry approximation and altitude control of ROVs," *Control Eng. Pract.*, vol. 29, pp. 135–146, 2014.

[9] F. Dukan, *ROV Motion Control Systems*. 2014.

[10] D. de A. Fernandes, A. J. S??rensen, K. Y. Pettersen, and D. C. Donha, “Output feedback motion control system for observation class ROVs based on a high-gain state observer: Theoretical and experimental results,” *Control Eng. Pract.*, vol. 39, pp. 90–102, 2015.

[11] N. Q. Hoang and E. Kreuzer, “Adaptive PD-controller for positioning of a remotely operated vehicle close to an underwater structure: Theory and experiments,” *Control Eng. Pract.*, vol. 15, no. 4, pp. 411–419, 2007.

[12] T. E. Laidig, L. M. Krigsman, and M. M. Yoklavich, “Reactions of fishes to two underwater survey tools, a manned submersible and a remotely operated vehicle,” *Fish. Bull.*, vol. 111, no. 1, pp. 54–67, 2013.

[13] L. Angeletti *et al.*, “New deep-water cnidarian sites in the southern Adriatic Sea,” *Mediterr. Mar. Sci.*, vol. 15, no. 2, pp. 263–273, 2014.

[14] A. Freiwald, L. Beuck, A. Rüggeberg, M. Taviani, and D. Hebbeln, “The White Coral Community in the Central Mediterranean Sea Revealed by ROV Surveys,” *Oceanography*, vol. 22, no. 1. pp. 58–74, 2009.

[15] T. I. Fossen, *Guidance and control of ocean vehicles*. Wiley, 1994.

[16] S. Soylu, A. A. Proctor, R. P. Podhorodeski, C. Bradley, and B. J. Buckham, “Precise trajectory control for an inspection class ROV,” *Ocean Eng.*, vol. 111, pp. 508–523, 2016.

[17] J. H. Goh, a Shaw, and a I. Al-Shamma’a, “Underwater wireless communication system,” *J. Phys. Conf. Ser.*, vol. 178, p. 012029, 2009.

[18] D. D. A. Fernandes, A. J. Sørensen, and D. C. Donha, “Path generation for high-performance motion of ROVs based on a reference model,” *Model. Identif. Control*, vol. 36, no. 2, pp. 81–101, 2015.

[19] S. A. Salman, S. A. Anavatti, and T. Asokan, “Adaptive fuzzy control of unmanned underwater vehicles,” vol. 40, no. April, pp. 168–175, 2011.

[20] M. Hosseini and S. Seyedtabaii, “Robust ROV path following considering disturbance and measurement error using data fusion,” *Appl. Ocean Res.*, vol. 54, pp. 67–72, 2016.

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