Interacting Propeller Thrust for Navigating Omni-Directional Remotely Operated Vehicle

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Abstract. The role of underwater vehicles in surveying, observation, search and rescue activities are increasing along with the development of the underwater positioning technology, such as sonar technology, underwater modem, etc. These technology help to develop the navigation algorithms, such intelligent system are developed in operating the vehicle autonomously or controlled. The Remotely Operated Vehicle (ROV) is equipped four fixed horizontal propellers installed at 45-degree angle to axis and one vertical propeller. The propellers are controlled simultaneously to drive the vehicle in multi-direction. Mapping movement strategy of interacting propeller were studied to control the vehicle’s movement and increase the of ROV performance.

1. Introduction

Underwater vehicle consists of two types of design based on how the vehicle operated; remotely operated and autonomous. The remotely operated vehicle (ROV) operated from surface ship through tether cable and it has a limited distance and restricted to the length of the tether cable. Autonomous underwater vehicle (AUV) is designed to operate autonomously and it has a limited operation time by the life time of the battery. Both vehicles are named Underwater Unmanned Vehicle (UUV), equipped an advanced control system regard to the objective task of the vehicle as a work class vehicle or survey class vehicle.

Performance of underwater vehicle is highly depending to the vehicle’s design such as number of propellers and the control strategy to drive the propellers. Under operation condition, the vehicle could be influenced by various forces act internally or externally. Internal forces resulted by the weight distribution and the buoyancy forces, and interacting propeller forces, while external forces resulted by the dynamic of the water fluid around the vehicle. Interaction of the whole forces resulted in a resultant force that will determine the vehicle movements, speed, and its direction. Another side, the design of the vehicle is highly determined by the task of the vehicle. The vehicle with single task mostly applies a fixed device while the vehicle with various task designed to be able to install various equipment for different tasks [1]. The design with different task has a different shape but it should be designed properly to reduce the effect of stability and the vehicle’s performance.

There are several scenarios how the vehicle or robot moves in water, among others; propulsion system resembles a fish fin model, robot that resembles snake motion in water. However, generally the survey and work-class type vehicles are driven using propellers. The number of propellers used varies according to the vehicle design and navigation scenario embedded in the vehicle. The vehicles for survey class generally use 1 up to 3 propellers. The work-class vehicles use more propellers. The number of
propellers used is based on the moving vehicle scenarios and to give the vehicle an ability to withstand the force from the currents and keeping position ability [2][3][4].

The pressure force acting on the surface of the vehicle increases with the depth proportionally. The vehicle is designed to have a good strength to the water pressure. The increase of depth 1.0 meter the increase force 1.0N per area in cm². The vehicles that weight slightly lower than the displacement weight tends to float the vehicle. It requires a navigation mechanism that governs the vehicle to be at the desired depth using horizontal fins. Using fins is a way to keep the vehicle moves at certain depth and speed continuously. The vehicle moves continuously to sustain force maintaining vertical movement. The vehicle also can be equipped with ballast system to adjust the vehicle weight equal to the water displacement weight by pumping water in to or out to the ballast tank.

In 1950s and ‘60s, the early design of ROV developed to have ability for recovery operation and to perform seabed rescue. The operation depth up to 10,000 feet, could be equipped with a various mechanical tools and sensors, fitted with high resolution digital cameras, sonar and a fibre optic which can combine up to eight channels of video, sonar, USBL (ultra-short baseline) positioning data, serial data communications and navigation data on a single fibre optic.

Generally, underwater vehicle can be divided in two types; Autonomous Underwater Vehicle (AUV) and Remotely Operated Vehicle (ROV). An autonomous underwater vehicle (AUV) is a robot which travels underwater without requiring direct input from an operator. In 1990s, there are many designs of AUV were developed for scientific, bottom surveys, and pipeline survey operations. The vehicle has capabilities of depth ratings up to 6,000m [5].

In 2013, Benjamin developed a circular ellipse AUV equipped with three propellers using servo. the propeller direction can be rotated at an angle exceeding 180 degrees, with moving ability in three-dimension to all directions or omni-directional movement[6].

Another typical vehicle that can be driven from the operator at surface vehicles is a remotely operated underwater vehicle, ROV. The vehicle used as work-class vehicle in deep water industries such as offshore oil and gas. The vehicle is connected to a surface ship by a buoyant tether or with a load-carrying umbilical cable. The umbilical cable is an armoured cable that contains a group of electrical conductors and fibre optics that carry electric power, video, and data signals from the vehicle and vice versa. In high-power applications, most of the tools and equipment are powered by hydraulic system. The system used for propulsion and power equipment such as torque tools and manipulator arms. Most ROVs are equipped with at least one video camera and light, some sensors to expand the vehicle’s capabilities such manipulator or cutting arm, water samplers, and instruments that measure water clarity, water temperature, water density, sound velocity, light penetration, and temperature.

After years, most ROV perform for offshore oil and gas industry with so-called “work-class” ROVs. The vehicle became essential tools in the 1970s and ‘80s when the operation of the vehicle exceeded the human divers. Today, the design of ROV developed to provide operation in the construction of sub-sea oil and gas in their subsequent inspection, repair and maintenance and very hugely in terms of depth rating, size, complexity and capabilities.

The typical design of ROV comprises a large of floatation pack above to provide the necessary buoyancy and high stability. Various electrical power systems are attached for operation such as torque tools, cutter and arm manipulators include the main propulsion system. Electrical power used to drive the hydraulic pump that is used for propulsion as an alternative to the more normal electrically power thruster [7].

2. Concept Design of ROV

The concept of the developed ROV has an omni-directional movement ability. With this ability, the vehicle can conduct survey and observation activities without tactical diameter during maneuver. The vehicle can move to sideways, backward, forward or move at certain angle direction. This vehicle designed to be equipped additional equipment at the bottom if necessary, such robotic arm. It is different to omni-directional vehicle designed by Benjamin in 2013 where the vehicle used for survey and monitoring with three rotatable propellers [6].

Two important parts considered in the design of the vehicle to be stable are position of the center of gravity and center of the buoyancy force. Both determine the vehicle's stability characteristic, where the
vehicle's stability is an ability of the vehicle to return to the equilibrium position when there any external force or moment disturb. Good stability when the center of gravity is underneath the center of buoyancy force and the longer distance between center of gravity and center of buoyancy the higher moment stability. Therefore, the vehicle designed to place the buoyant structure at the top of the vehicle and weights at the bottom.

In the design of propeller, the vehicle uses ducted propeller where the ducted propeller has advantages than the conventional propeller. The ducted propeller can increase the efficiency of the thrust propeller, has lower diameter compare to non-ducted propeller, and the ducted propeller can protect the propeller from other objects. Ducted propeller installed on the main structure with fixed mounting angles. However, besides the fixed angle mounted on the structure, rotatable propeller also able to be installed that can decrease the number of propellers installed for application to multi-direction movement. In this paper, the fixed propeller angle has a simpler in design and installation.

In another side, the vehicle designed to have a capability to keep the vehicle’s position in stable position even under force disturbance from current. The vehicle also designed has the same weight with the buoyancy force that can ease the vehicle move vertically.

Design of the ballast system also consider the total weight required and the centre of gravity. Therefore, the design of weight distribution and buoyancy for every part are calculated properly that it will not decrease the vehicle’s stability. The higher stability can make the vehicle very stiff and decrease the ability of the vehicle to rotate in pitch and roll motion. The concept design of the ROV as shown in figure1.

![Figure 1. Developed Design of ROV](image-url)

In this research, this early ROV designed to operate in 100m under the water surface. The dimension of the developed design has 58.60cm length, 42.21cm breadth and 32.60cm high. The model equipped five propellers with 7.0cm diameter, one buoyant tank at top, four dry batteries placed at bottom as additional source power and to increase the stability. Four propellers are installed at each corner with 45 degrees angle to the axis and one propeller placed vertically at the buoyant tank. The propellers used to control the vehicle motions in six degrees. The design speed of vehicle is 0.5m/s.

2.1. Propulsion System

Propulsion systems of the ROV are designed using five propellers. Four propellers are used to drive the vehicle in horizontal and longitudinal direction. One propeller is placed at the upper side in line with the centre of gravity to drive the vehicle vertically. Four propellers installed at each corner and crossing each other at 45 and 135 degrees to its directional axis to drive the robot move in multidirectional.

The brushless motors were used as the prime mover of the propellers. The vehicle’s movement resulted by vectored forces of the propeller’s thrust and it designed to have ability in omni-directional movement. The vehicle uses ducted propeller with three blades (Figure 2) with some advantages as follows; It has more efficient in producing thrust than a conventional propeller [8], at the same static thrust, a ducted propeller has a smaller diameter than conventional propeller, and Ducted propeller offers enhanced safety from contact to others object.
Figure 2. Ducted propeller with 3 blades

2.2. Navigation ROV

The navigation system of the vehicle uses joystick as the console for motion command signal. Four propellers used for transversal and longitudinal movement while one propeller for vertical movement. All propellers controlled simultaneously follow the signal from the joystick. Combinations of navigation movement and propeller thrust direction in navigation are shown in Figure 3 and 4.

Figure 3. Navigation concept of ROV, yellow arrow is propeller thrust direction and white arrow is vehicle movement directions. (a) surge (b) sway, (c) Heave down, (d) combining surge and sway, (e) yaw and (f) heave up.

Figure 4. Navigation concept of ROV, yellow arrow is propeller thrust direction and white arrow is vehicle movement directions. (a) Combining surge and heave (b) combining sway and heave (c) asymmetric pitch, and (d) asymmetric roll.

In general, navigation concept of the vehicle designed to have ability moving in six degrees of freedom; surge, sway and heave (translation motion) and roll, pitch and yaw (rotation motion). Combining those motion, the vehicle can move in Omni-directional movement. However, roll and pitch motion are limited due to high static stability of the vehicle. Installation propeller at each corner of the vehicle consider the centre of vehicle’s movement where propeller installed at proper position and angle that will not result a contra thrust between propellers. Positioning the propeller in such can affect the performance of propeller thrust and moment ineffectively.
3. Kinematic Model

An underwater vehicle with omni-directional capability was developed by Meyer at.al.[6]. The vehicle equipped three propellers with servo motor to rotate the propellers direction. The propeller thrust direction were designed can rotate automatically to provide the vehicle moves in multi direction. In this ROV design, the propellers attached at fixed angle; 45 and 135 degrees. The vehicle movement follows the Joystick command by rotating each propeller in a particular rotation. Propeller rotation is calculated based on a combination of the Joystick signal in x-signal and y-signal. The ratio between the signals is the angle of the direction of the vehicle direction and the resultant signal is a command to provide the propeller thrust. The combination signals are calculated to provide the number of rotations for each propeller. The calculation of propeller rotation is done using the kinematic model of the vehicle written as follows;

\[
\begin{bmatrix}
F_x \\
F_y \\
F_z \\
M_x \\
M_y \\
M_z
\end{bmatrix} =
\begin{bmatrix}
ca & c\beta & ca & c\beta & 0 \\
-sa & s\beta & -sa & s\beta & 0 \\
0 & 0 & 0 & 0 & 1 \\
-dx,sa & dx,s\beta & 0 & 0 & dz_5 \\
0 & dy,c\beta & dy,c\alpha & 0 & dz_5 \\
dy,c\alpha & -dy,c\beta & -dy,c\alpha & -dy,c\beta & 0
\end{bmatrix} \begin{bmatrix}
T_1 \\
T_2 \\
T_3 \\
T_4 \\
T_5 \\
T_6
\end{bmatrix}
\]

\[
[T] = [A][T] \quad [F] = [A^{-1}][F] 
\]

In equation (1), transformation matric has 6 columns and 5 rows dimension. Regularly, there no inverse matric derived using a non-square matric. However, the inverse matric could be generated using a quasi-inverse matric for non-square dimension as shown by Ruben [9]. Then, the thrust [F] for all propeller transformed in to thrust [T] and the number of rotations for all propeller are obtained.

The strategy of navigating the vehicle analysed and the ratio of resultant force of interacting propellers obtained for all angles based on the angle of mapping motion required. Based on the kinematic model, the relation between angle of motion and the force ratio are showed as follows;

\[
T_i = K_T \times D_i^4 \times n_i^2 \\
n_i = \sqrt{\frac{T_i}{K_T \times D_i^4}}
\]

(2)

Where \(F, M, T\) are force, moment and propeller thrust respectively, \(c\) is cosines, \(s\) is sinus, \(d\) is horizontal propeller arm to centre of rotation, \(l\) is vertical propeller arm to centre of rotation, \(n\) is propeller rotation and \(K_T\) is propulsion coefficient of thrust. \(\alpha, \beta\) are angles of propeller where \(\alpha\) is angle for propeller 1 and 3, and \(\beta\) is angle for propeller 2 and 4. The direction of rotation motion symbols are \(\phi, \theta, \psi\) for roll, pitch, and yaw respectively.

The strategy of navigation the vehicle, drive the motor simultaneously to propel the vehicle at certain motion direction in such scenarios are;
Simulation of the navigating scenarios through interacting thrust propeller only consider the thrust propellers. Forces resulted by the vehicle’s motions were not considered. Thrust propeller linearized in range 0.0 and 1.0-unit force. The negative value indicating the propeller rotation is counter clockwise and positive value indicating the propeller rotation is clockwise. Then, all movement scenario found as follows.

Table 1. Interacting propeller thrust, force and moment in each axis

| Scenario | P1 | P2 | P3 | P4 | P5 | Fx  | Fy  | Fz  | Mx  | My  | Mz  |
|----------|----|----|----|----|----|-----|-----|-----|-----|-----|-----|
| 1        | 1  | 1  | 1  | 1  | 0  | 2.83| 0.00| 0.00| 0.00| 0.00| 0.00|
| 2        | -1 | 1  | -1 | 1  | 0  | 0.00| 2.83| 0.00| 0.00| 0.00| 0.00|
| 3        | 0  | 0  | 0  | 0  | 1  | 0.00| 0.00| 1.00| 0.00| 0.00| 0.00|
| 4        | 0  | 1  | 0  | 1  | 0  | 1.41| 1.41| 0.00| 0.00| 0.00| 0.00|
| 5        | -1 | 1  | -1 | 1  | 1  | 0.00| 2.83| 1.00| 0.00| 0.00| 0.00|
| 6        | -1 | -1 | -1 | -1 | 1  | -2.83| 0.00| 1.00| 0.00| 0.00| 0.00|
| 7        | 0  | 0  | -1 | 1  | 1  | 0.00| 1.41| 1.00| 0.00| 0.00| 0.00|
| 8        | -1 | 0  | 0  | -1 | 1  | -1.41| 0.00| 1.00| 0.00| 0.00| 0.00|
| 9        | -1 | -1 | 1  | 1  | 0  | 0.00| 0.00| 0.00| 0.00| 0.00| 0.85|

In the Table-1 shows the maximum force moving forward and sideward are 2.83-unit force, drift is 1.41-unit force for each horizontal axis by four propellers. The maximum moment resulted at yaw motion with maximum 0.83-unit force. At the scenario-7 and 8 show no moment resulted as the propeller installed at the same high of the vehicle's center gravitation.

Based on the navigation scenario, interacting propeller forces and moments were simulated with scenario from moving forward (scenario1) to Sideward (scenario.2), Upward (scenario.3), Sideward-front (scenario.4) as shown in the following figures.
Figure 6. Forces in X, Y axis and the force resultant for the vehicle navigation from scenario 1 to scenario 2. The propeller 1 and 3 thrust simulated gradually change from +1.0 to -1.0 while propeller thrust 2 and 4 are +1.0.

Figure 7. Forces in Fx, Fy, and Fr when the vehicle navigates from scenario 1 to scenario 3. The propeller 1, 2, 3, and 4 thrust were simulated change gradually from 1 to 0.0 while propeller thrust 5 changes gradually from 0.0 to 1.0.

Figure 8. Forces in Fx, Fy, and Fr when the vehicle navigates from scenario 1 to scenario 4. The thrust of propeller 1 and 3 were simulated change gradually from 1 to 0.0 while propeller thrust 2 and 4 were constant at 1.0.

4. Experimental
The experiments were conducted in the small pool three metres diameter. This test were conducted to determine the ability of the propeller system drives the vehicle in accordance with the instructions given
by JoyStick. The vehicle testing includes; manoeuvring to the right, manoeuvring to the left, drift to the right and sway. The tests were shown in the following figures.

**Figure 9.** The vehicle moves from top to left. The vehicle manoeuvres with direction of the moving from 270 degrees (facing to $-y$ axis) to 180 degrees (facing to $-x$ axis).

**Figure 10.** The vehicle moves from top to right. The vehicle manoeuvres with direction of the moving from 270 degrees (facing to $-y$ axis) to 90 degrees (facing to $+x$ axis).

**Figure 11.** The vehicle drift from the centre position to the top left. The vehicle moves 135 degrees with the facing direction to the $-x$ axis. The vehicle keeps the facing angle constantly.

**Figure 12.** The vehicle drift from the centre position to the bottom left. The vehicle moves to 225 degrees with the facing direction to the $-x$ axis. The vehicle keeps the facing angle constantly.
Figure 13. The vehicle drift from the centre position to the bottom right. The vehicle moves to 315 degrees with the facing direction to the +x axis. The vehicle keeps the facing angle constantly.

Figure 14. The vehicle drift from the centre position to the bottom. The vehicle moves to -y axis while the facing direction to the –x axis. The vehicle keeps the facing angle constantly.

Figure 15. The vehicle drift from the centre position to the top. The vehicle moves to +y axis while the facing direction to the –x axis. The vehicle keeps the facing angle constantly.

5. Discussion
The navigation simulation that has been carried out showed the force or moment resulted in each scenario. When the vehicle moves forward, the resultant force resulted at a maximum force of 2.83 units force and 0.83-unit moment. The resultant force resulted was 70% of the total thrust given by all propellers. However, the vehicle has ability to move in omni-directions of movement except pitching and rolling were in the simulation of force and moment interaction shows there no moment for both motions. The test conducted in the small pool with 3.0 metres diameter. Based on the tests of the vehicle for manoeuvring, drift, and sway showed the vehicle can follow the scenario. The signal of propeller drivers generated by the Joystick’s signal, the microcontroller calculated and feed the signal to the motor driver.

6. Conclusion
The simulation of interacting force and moment based on the navigation scenario and the experiment results showed the vehicle has ability to move in omni-directional motion while rolling and pitching motion are not available. The experiments showed the vehicle manoeuvred to left and right, sway and
drift movement. The kinematic model and the generated inverse solution matrix showed a good response to the vehicle movement.

7. **Future work**
This research will continue on developing the robust control system for vehicle’s keeping position under current disturbance. Numerical simulation and experimental will be performed to validate the simulation results at the end of this study.

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