Position and Velocity Analysis of Open and Closed loop system using various Controllers in Underwater ROV - ORCA for Stabilized Navigation

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Abstract: Remotely Operated Vehicle (ROV) is an unmanned vehicle operated using a tether for navigation, control and underwater missions. ORCA is a student developed budgetary ROV which was indigenously developed exclusively for the underwater inspection and survey application purpose. Due to unstable operating environments, dynamic modeling, simulation of the ROV is essential in order to understand the stabilized navigation and movements of the vehicle at required depth of operation. ORCA has been mathematically modeled based on Newtonian dynamics in the Simulink platform to simulate the position and velocity responses of the vehicle. Different control system models were compared - open loop and closed loop systems (with controllers P, PI, PID). To investigate the impact of different underwater forces on the vehicle, an open loop system was employed. The closed loop system was designed to enhance the ROV's navigation capabilities. Finally, the closed loop system proposed with a PID controller was found to be more suitable for stabilizing the ORCA ROV.

Keywords: *ROV, Controller, P, PI, PID, Degrees of Freedom, Open Loop System, Closed Loop System*

I. INTRODUCTION

Remotely Operated Vehicles

There are several types of underwater robots including Autonomous Underwater Vehicles (AUVs), Remotely Operated Vehicles (ROVs), Solar-powered Autonomous Underwater Vehicles (SAUVs) etc. ROV are underwater robots controlled using tethers widely used for underwater missions, survey and inspections. There are two types of undersea vehicles, according to the Committee on Undersea Vehicles and National Needs. The first is a vehicle that is capable of carrying people, or what the Committee refers to as a "manned" vehicle. The second vehicle is incapable of transporting either "unmanned" or human vehicles. [6]. The exploration of ocean depths can be carried using an unmanned ROV which is a highly maneuverable vehicle. The ROV are operated remotely from the sink vessel floating on the ocean water surface. In addition to a wide range of scientific applications and expeditions like ocean exploration, they are commonly employed for industrial objectives like the structural testing of offshore platforms and the internal and external inspection of underwater pipelines. Because ROVs can do tasks that need a high degree of precision, they are now receiving more attention in the development of underwater robots than AUVs.

ROVs consist of multiple propeller thrusters pointing in various directions [10] for a desired fixed directional movement according to the user's input. The direction of rotation of these thruster blades influences the movement of the vehicle. The driven force of backward and forward, right and left turn, downward and upward is supplied by the thrusters, also known as the six degrees of freedom. The power supply's capacity is influenced by the number of thrusters; thus an underwater robot weighs more when its power supply is huge. There are various subsystems in an ROV [9]. The primary component includes the main processing unit, where instructions are fed and then converted into a physical output - positions and movements of the ROV. The size of the ROV varies as micro ROV, mini ROV, general ROV, inspection class ROV, heavy work class ROV with respect to various applications [13-14].

About the ORCA ROV

ORCA is an ROV with dimensions of 500 x 350 x 210 mm which weighs about 10.247 kg. It is equipped with sensors like temperature sensor, pressure sensor, leak sensor, Inertial Measurement Unit and a camera for underwater inspection and survey applications of up to a depth of 300 meters. The vehicle's body consists of two sealed acrylic enclosures, carrying the electronics systems and the battery. The embedded electronic system integrated with sensors provides the desired motion of the ROV in underwater that controls and achieves the desired movement of the vehicle as per the joystick command to the thrusters through the tether cable. The whole ROV system is powered using the 14.8V,18Ah Li-ion battery enclosed in the sealed hull. A high performance HG1120 micro-electro-mechanical system (MEMS) inertial measurement unit (IMU) is used. The HG1120 includes MEMS gyroscopes, accelerometers and magnetometers, making it a 9 Degrees Of Freedom (DOF) IMU. In addition, the HG1120 employs an internal environmental isolation system to attenuate unwanted inputs commonly encountered in real world applications. Figure 1 shows the top view of ORCA inland and waterbody.

Fig. 1: ORCA ROV structure

Navigation of A Remotely Operated Vehicle

The two frames of reference that are typically taken into account by all systems are the fixed or inertial frame [8] and the frame that is attached to the moving body and is presumed to move with it. The ROV can move in six degrees of freedom - three translational motions and three rotational motions. Translation motions involve moving along the different axes X, Y and Z

- Heave: Moving up and down along the Y axis,
- Surge: Moving forwards and backwards along the X axis.
- Sway: Moving left and right along the Z axis.

The rotational motions involve turning in order to face a different axis.

- Pitch: Moving between X and Y,
- Yaw: Moving between X and Z,
- Roll: Moving between Z and Y [7].

The pilot can then perform manoeuvres by combining any of these movement characteristics.

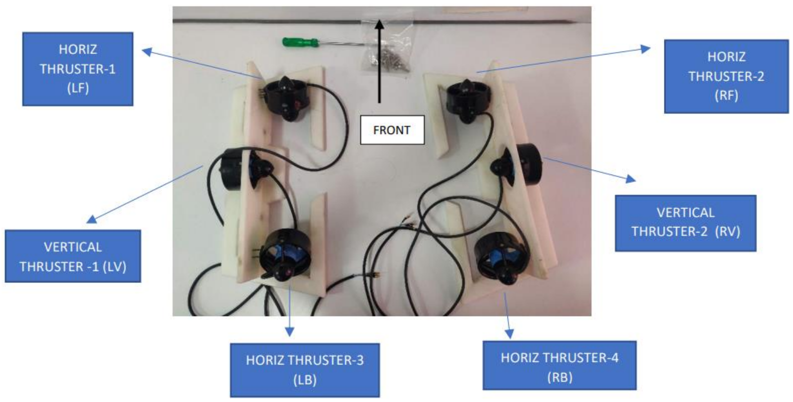

Fig. 2: Positioning of thrusters in ORCA ROV

The thrusters utilize a vector-based approach in most of the ROVs based on the rotational movement of the thrusters' blades as shown in Figure 2. The DOF of the ROVs depend on the arrangement of thrusters in the structure. Underwater robots are frequently shaped like torpedoes, with a cylindrical form. Underwater robots may move at high speeds down the horizontal axis and drop diagonally with the use of rudders when they adopt this design, which is more commonly utilized. Certain additional kinds of torpedo-shaped underwater robots use extra thrusters in place of rudders [11,12]. Table 1 shows the six degrees of freedom of ORCA.

Table 1: Depicts the 6 Degrees of Freedom of ORCA with respect to the thruster blades direction of rotation(Anticlockwise - ACW and Clockwise - CW)

DoF	Left Front	Right Front	Left Back	Right Back	Right Vertical	Left Vertical
Surge - Forward	CW	CW	CW	CW	0	0
Surge - Backward	ACW	ACW	ACW	ACW	0	0
Sway - Left	ACW	CW	CW	ACW	0	0
Sway - Right	CW	ACW	ACW	CW	0	0
Heave - Upward	0	0	0	0	CW	CW

Heave - Downward	0	0	0	0	ACW	ACW
Roll - Clockwise	0	0	0	0	CW	ACW
Roll - Anti Clockwise	0	0	0	0	ACW	CW
Yaw - Clockwise	CW	ACW	CW	ACW	0	0
Yaw - Anti Clockwise	ACW	CW	ACW	CW	0	0

Stability of the Underwater Vehicle

The most important component for a stabilized movement of the ROV is the controller. The controller tends to reduce the variations and deviations in the untargeted DOF other than principle direction of motion given by the pilot. The mechanism of a controller is to minimize the difference between the system's actual input and the feedback value. By lowering the steady-state error, controllers typically increase steady-state accuracy. Stability increases in tandem with improvements in steady-state accuracy. Additionally, they aid in lessening the undesired offsets generated by the system, which cause the ROV to move in an undesirable direction.

Effectiveness of P, PI, PD and PID controllers in the Pressure Regulating Valve of a trisonic blowdown wind tunnel was studied [1]. The major objectives in the study included reducing the overshoot and undershoot conditions and to improve the settling time, rise time, steady state error etc. The usage of the PID controller achieved the objectives and was more efficient than the others.

A comparative study of Proportional (P), Proportional Integral (PI), and Proportional Integral Derivative (PID) controllers were carried for speed control of induction motor [2]. It was concluded that P controllers can stabilize only the 1st order unstable processes. PID controllers can be utilised for higher order capacitive processes, while PI controllers can be used to prevent significant noise. PID achieved the best response among all. In [4], Hybrid Fuzzy PI controller was proposed. The controller was tested on a Brushless DC motor (BLDC motor) which improved the performance of motor and operating conditions such as settling time, rise time, overshoot percentage and stability phenomenon etc. A PI-PD control methodology was used in [5]. These controllers were found to be spontaneous, since it incorporates two different control modes together. This controller was then further tuned using a proposed tuning method in the study to achieve the desired control objectives. There are various controllers used nowadays for different real-time applications. This study focuses on the P, PI and PID controllers used in closed loop control systems for underwater ROV.

Proportional (P) controller:

It is the most straightforward and user-friendly structure for putting linear control systems into practice. P-only control reduces output fluctuations, but it doesn't always move the system in the desired direction. In comparison to most other controllers, it offers a quicker response [3].This controller is useful when the error is under a specific limit. A proportional controller is insufficient to handle the error generated if the error surpasses the threshold. Equ. (1) shows the mathematical modeling of the P controller. It generates an output that is proportionate to the current error value by using the gain Gp. When the proportionate gain (Gp) is elevated, the system experiences instability.

$$\mathrm{O(t) = Gp * [i(t) - f(t)]} \qquad (1)$$

Where,

$\mathrm{i(t)}$ = Reference Input Signal
$\mathrm{f(t)}$ = Feedback Signal
Gp= Proportional Gain

However, P controllers do not have memory or forecasting ability to improve the regulation.

The Advantages of P - mode controller is: Easy implementation, High loop gain is obtained, Faster response obtained even from slower and damped response and reduces the steady state error.Similarly, the disadvantages of P - mode controller are,offset error is present, for a large gain, instability is increased, Increases the maximum overshot of the system.

Proportional-Integral (PI) controllers:
These are more widely used. If the proportional gain is high in case of P-mode controller, then the system becomes unstable. To make the system performance stable, integral action is to be considered as in the PI-mode controller. It considers both the magnitude of the system error signal and the integral of this error also.When a process returns the same result with the same set of inputs and disturbances taken into account, it is considered non-integrating and requires a PI control model [4]. The value of the controller output O(t) is fed into the system as the manipulated variable input as shown in Equ. (2).The integral controller is used to reduce the steady state error. However, a P controller is essential for integrating processes.

$$O(t) = Gp * \{e(t)\} + Gi * \{\int e\,(t)\,dt\} \qquad (2)$$

where,

$\mathrm{e(t)}$ = Error signal = $\mathrm{i(t) - f(t)}$
$\mathrm{i(t)}$ = Reference Input Signal
$\mathrm{f(t)}$ = Feedback Signal
Gp = Proportional Gain
Gi = Integral Gain

The Advantages of PI-mode controllers are: Reset controllers, as they are often called, reduce steady-state error and enable the controlled variable to be brought back to the precise position, they respond to deviations continuously and Higher sensitivity.The disadvantages of PI-mode controller are,high initial overshoot, slower response to input than P controllers, unstable if there are sudden disturbances.

Proportional-Integral-Derivative (PID) controllers:
This is the most commonly used controllers in many industries for real time applications. A PID controller combines the benefits of proportional, derivative and integral control actions. Various advantageous features are obtained through this combination

- fast response if the input of controller is changed (D mode feature),
- error tends to towards zero with increase in control signal (I mode feature) and
- suitable action inside control error area to eliminate the oscillations and fluctuations (P mode feature).

The proposed PID controller block diagram is shown in Figure 3 below

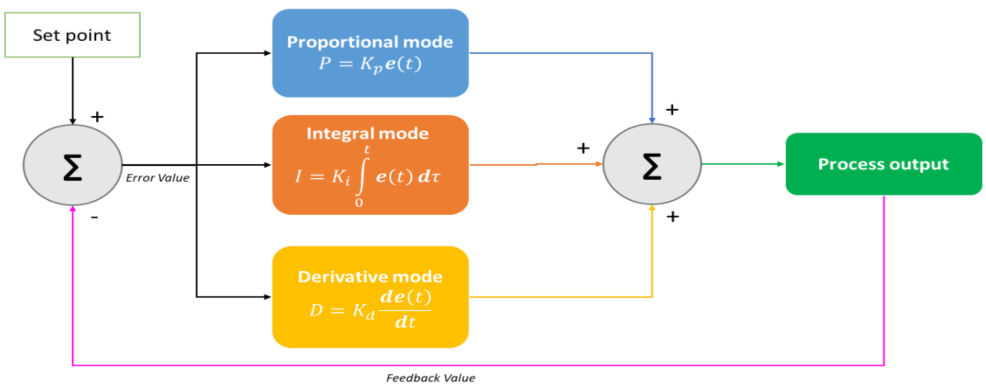

Fig. 3: Schematic representation of the proposed PID controller.

The controller can be mathematically modeled using Equ (3).

$$O(t) = Gp * (e(t)) + Gi * \int e(t)dt + Gd * d(e(t))/dt) + C \qquad (3)$$

Where,

Gp = Proportional Gain
Gi = Integral Gain
Gd = Derivative Gain

The advantages of PID - mode controller are, reduced overshoot, control loop response is faster, more robust to tuning errors and mismatches, Faster reaction to even unknown disturbances. The disadvantages of PID - mode controller are, it cannot be used in processes with abundant noise, cannot incorporate ramp-type set-point deviations, improper response to slow disturbances at the input end.

II. METHODOLOGY

The ORCA ROV is modeled based on Newtonian Dynamics in order to study the effects of various forces like centripetal force and Coriolis, restoring forces, hydrodynamic damping force and added mass in underwater. The position and velocity responses of the system are then simulated to understand the performance of the open loop system subjected to various perturbed conditions underwater.

Mathematical Modeling of ROV

Open Loop System:

The assumptions taken in account for mathematical modeling of the ORCA are

- The ROV is fully submerged in water with a rigid body.
- The effect of waves is neglected as the ROV is considered to be at a certain depth of the water body.
- The earth fixed frame of reference is inertial.
- It is assumed that the ROV is being used in inspection operation and ensure moving slowly at the required depth of operation.

The six degree of operation (6DOF) nonlinear equation of motion of ROV in body fixed frame required to mathematically model ORCA is given by

$$\mathbf{M}i + (i)i + \mathbf{D}(i)i + \mathbf{H_f}(\boldsymbol{\eta}) = \boldsymbol{\tau} \quad (4)$$

where

M is the matrix of mass inertia. This is sum of the added fluid inertia mass and rigid body inertia mass matrix.(i.e)$\mathbf{M} = \mathbf{M}_A + \mathbf{M}_{RB} \in \mathbf{R}^{6\times6}$

C(i) is the centripetal force matrix and Coriolis which contains the added mass and rigid body terms respectively, (i.e) $\mathbf{C}(i) = \mathbf{C}_A(i) + \mathbf{C}_{RB}(i) \in \mathbf{R}^{6\times6}$

(i)$\in \mathbf{R}^{6\times6}$ is the Damping matrix due to the surrounding fluid.

$\mathbf{H}(\boldsymbol{\eta}) \in \mathbf{R}^{6\times1}$ is used to describe the buoyancy and gravitational force on the ROV.

$\boldsymbol{\tau} \in \mathbf{R}^{6\times1}$ is the thrust vector or total force in a given DoF.

$\mathbf{i} = [\, \mathbf{u\ v\ w\ p\ q\ r}]\ \mathbf{T}$is the body-fixed velocity vector and

$\boldsymbol{\eta} = [\boldsymbol{\eta}1\ \boldsymbol{\eta}2]^T$ is the orientation vector and Earth-fixed position

where

$\boldsymbol{\eta}2 = [\varphi\ \theta\ \psi\ ]^T$ is the orientation vector of Euler angles and

$\boldsymbol{\eta}1 = [x\ y\ z\ ]^T$is the position vector.

The mass of the ROV is represented by rigid body mass inertia matrix (M_{RB}) which in turn represents the mass of the ROV and spread of the mass in different directions in terms of moment of inertia.

The inertial force acting on a rotating ROV within an earthly frame of reference is known as the Coriolis force. The ROV will move more slowly because of the hydrodynamic negating force created by the fluid moving around the vehicle as a result of the ROV's motion. When the fluid particles come into contact with the vehicle, they accelerate, which creates these forces and moments. Like "added" mass and inertia, their effect seems to be.

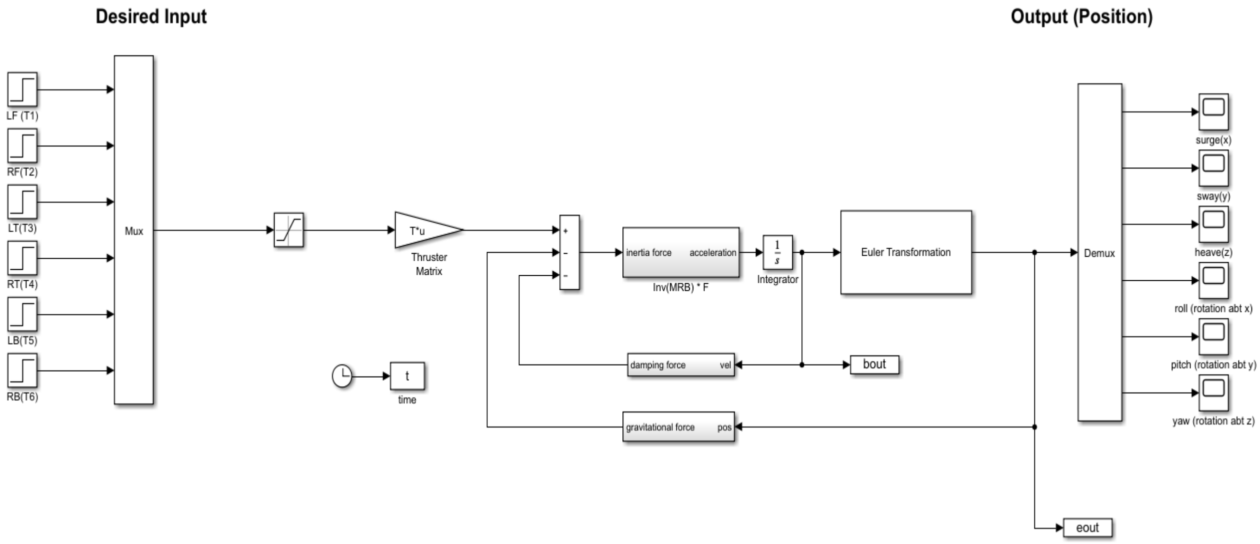

Fig. 4: Block diagram of the Open loop system of the ORCA in SIMULINK

The open loop system is modeled using MATLAB SIMULINK platform as shown in Figure 3. The proposed block diagram consists of

- Thrust configuration block,
- Inertial and added mass block,
- Coriolis and centripetal block,
- Gravitational force block and
- Euler transformation block.

The cause of nonlinearity of the model is because of the external forces that affect the stability and navigation of the system in the underwater environment.

$$\mathbf{i} = \mathbf{M-1}\{\boldsymbol{\tau} - [\mathbf{C}(i)i + \mathbf{D}(i)i + \mathbf{H}_f(\boldsymbol{\eta})]\} \qquad (5)$$

Equation (5) depicts the subsystems of the model in Figure 4. The acceleration vector is integrated to form the body-frame velocity vector and then further transformed into inertial frame position and orientation vector. By giving the input to the thrusters with their thrust values in kgf, the velocity and position responses are obtained for each of the DOF. These responses are analyzed to study the movement and deviations from the desired set value of the ORCA underwater system when inputs are provided through the joystick control.

Closed Loop System:

A PID controller (with P, I and D control modes) is added to the modeled Open Loop System to make it a closed loop system. The major difference between a closed loop and an open loop system is the presence of a negative feedback loop in the closed loop system which is absent in the open loop system model. Through comparison with the actual situation, closed loop systems are built to automatically achieve and maintain the intended output condition. This is achieved through the generation of an error signal which is the difference between the actual output obtained and the feedback signal.

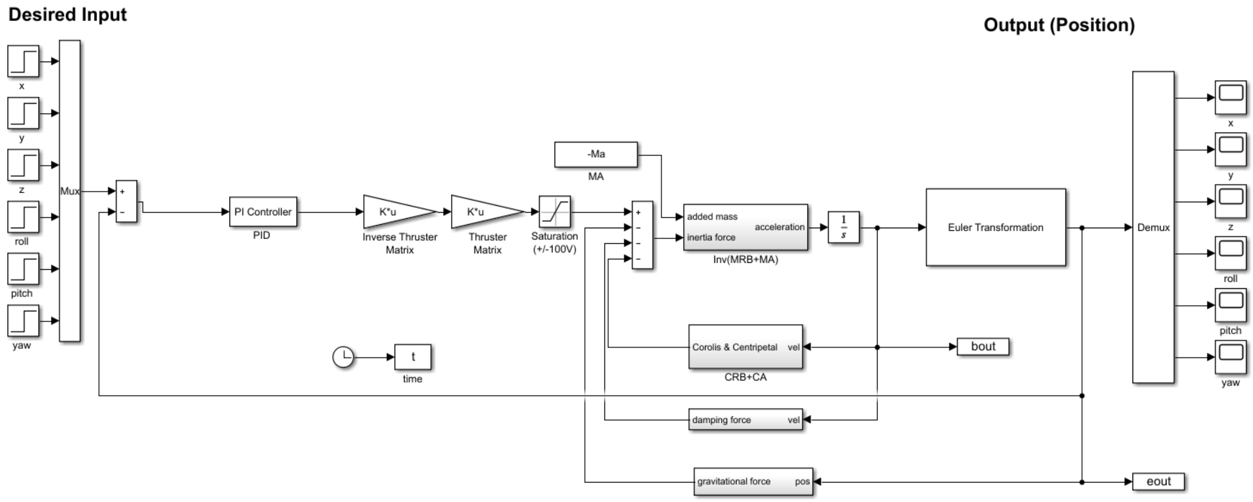

Fig. 5: Block diagram of the Closed loop system of the ORCA in SIMULINK.

The above Figure 5 shows the block diagram of a closed loop system with an additional component of a feedback system from the output to the input side - differing from the open loop system.

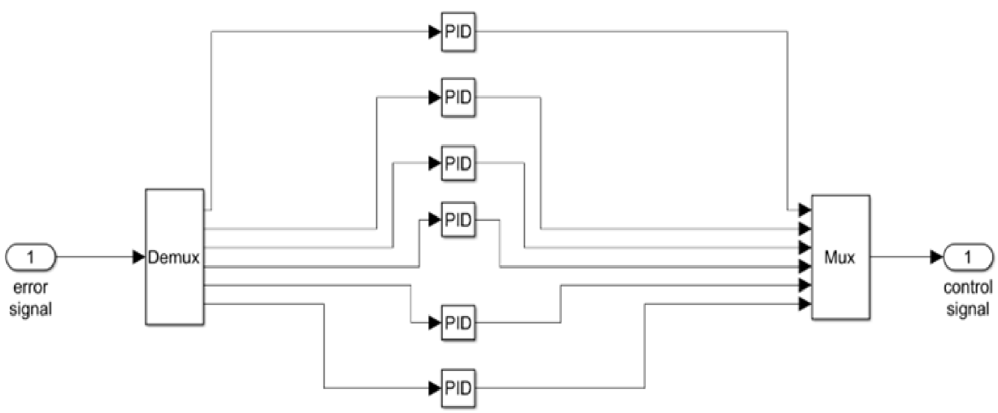

Fig. 6: Elaborated PID controller

All the three modes of the controllers were used to test the position and velocity responses of the closed loop system. The elaborated PID controller of figure 3 is shown in figure 6 below and is used for the study and analysis.

III. TUNING

For a PID controller, the tuning constant “K” depends on the response characteristics of the complete loop external to the controller. Thus, these parameters must be tuned for each application. The method of finding appropriate values for the integral, proportional, and derivative gains of a PID controller to satisfy the design requirements and attain the desired performance is called PID tuning.

Process of Tuning:

Keeping Ki and Kd in Equ (3) as zero, start with a low Kp value (P-gain) and increase it slowly until the performance of the system starts to deteriorate. Back off to a point just below this point. Examine the response obtained with the final Kp value to check for the problems of instability and steady-state error. The Dgain should be tuned if stability issues are the main concern while looking for a P-gain; if steady-state error issues are the main concern, the I-gain should be tuned.

IV. RESULTS AND DISCUSSION

Nonlinear Open Loop Position and Velocity Responses of ORCA

The ORCA system consists of six thrusters for providing movements in the horizontal and vertical plane. These thrusters are T200 models, and their maximum rotational forces are 4.53 kgf and 3.5 kgf in a clockwise direction & anticlockwise direction. For the simulations, shallow water channel is considered with density of 998.2 kg/m^3, a viscosity of 0.001003 Ns/m^2 and pressure 1.02 bar at 25℃ (room temperature). The inputs were given to the thrusters in the SIMULINK model (as kgf values) to simulate the different movements of the ORCA. Input was given at 25%, 50%, 75% and 90% of the maximum possible thrust value. For every input the time variation is from 10 seconds to 300 seconds, and the responses were obtained.

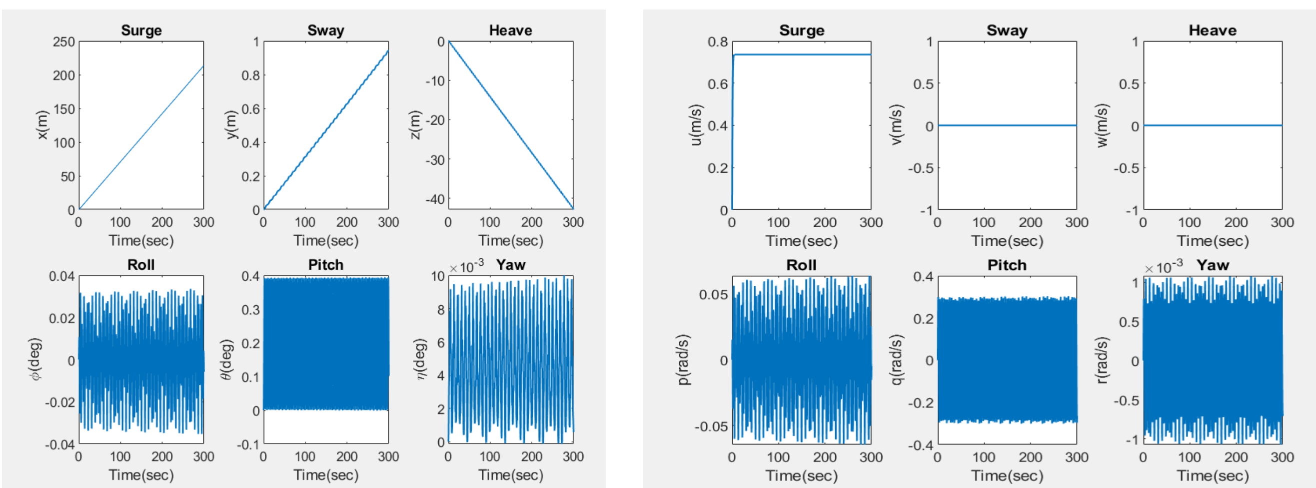

Fig. 7: Position and Velocity responses of Surge forward motion in an open loop system with 50% thrust values.

From Figure 7, it can be observed that the deviations are significantly higher in the untargeted degrees of freedom. This was simulated with 2.265 kgf thrust values given to the thrusters for a period of 300 seconds. The vehicle has moved about 210m in the targeted direction of motion - surge forward. In the other degrees of freedom, significant values and deviations were observed. Similarly, the same can be analyzed for the velocity response. The ORCA maintained a velocity of 0.75m/s from time 0 to 300s and minor disturbances were observed in the untargeted degrees of freedom as shown in Figure 7. A similar pattern was observed when simulated for other directions too.

Nonlinear Closed Loop Position and Velocity Responses of ORCA

ORCA simulations were performed with different controller modes (P, PI, PID) to obtain the velocity and position responses for the different DOF. The closed loop system provides a feedback loop mechanism to minimize the deviations in the output in the non-target degrees of freedom. The feedback system helps in reducing the errors generated in the output in comparison to the actual input provided.

From Figure 8, using the P controller, from the position response ORCA's movement was significant in the surge forward direction and only negligible variations in the other degrees of freedom from 0 to 300 seconds. Similar pattern can be seen in the velocity response - with significant contribution in the surge forward direction. Minor results were also observed in the other degrees of freedom.

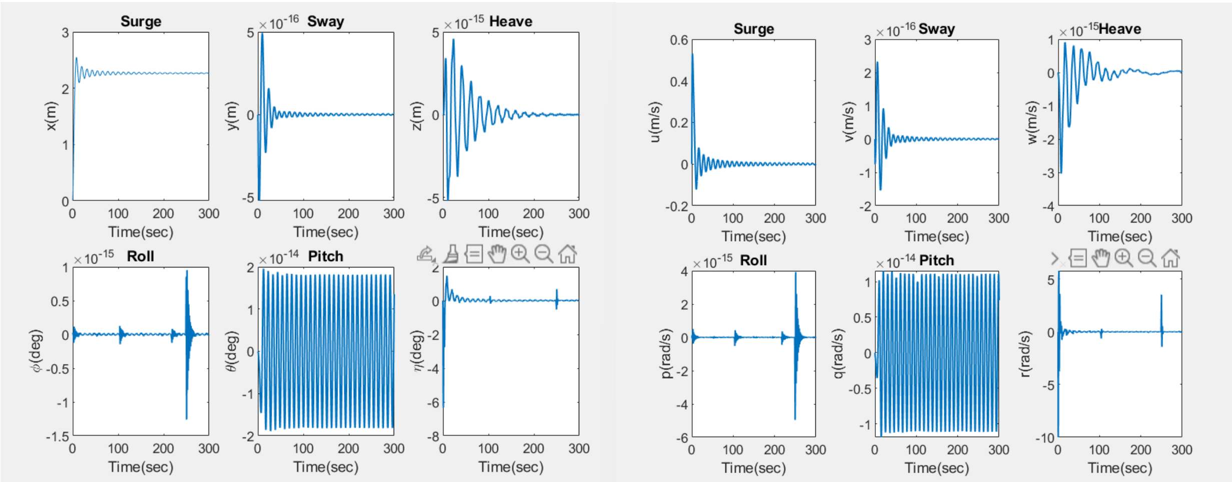

Fig. 8: Shows the position and velocity responses of Surge forward motion in a closed loop system (P controller (Kp = 4)) with 50% thrust values.

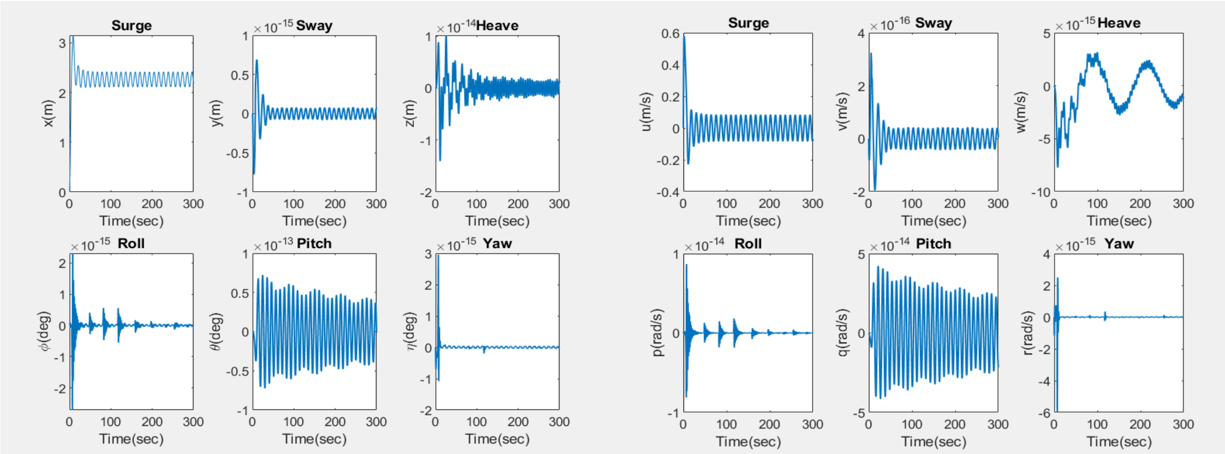

Figure 9: Shows the position and velocity responses of Surge Forward motion in a closed loop system (PI controller (Kp = 4, Ki = 0.5)) with 50% thrust values.

From Figure 9 the response of position and velocity of surge using the PI controller, it is seen that the results are continuous with respect to some oscillations.

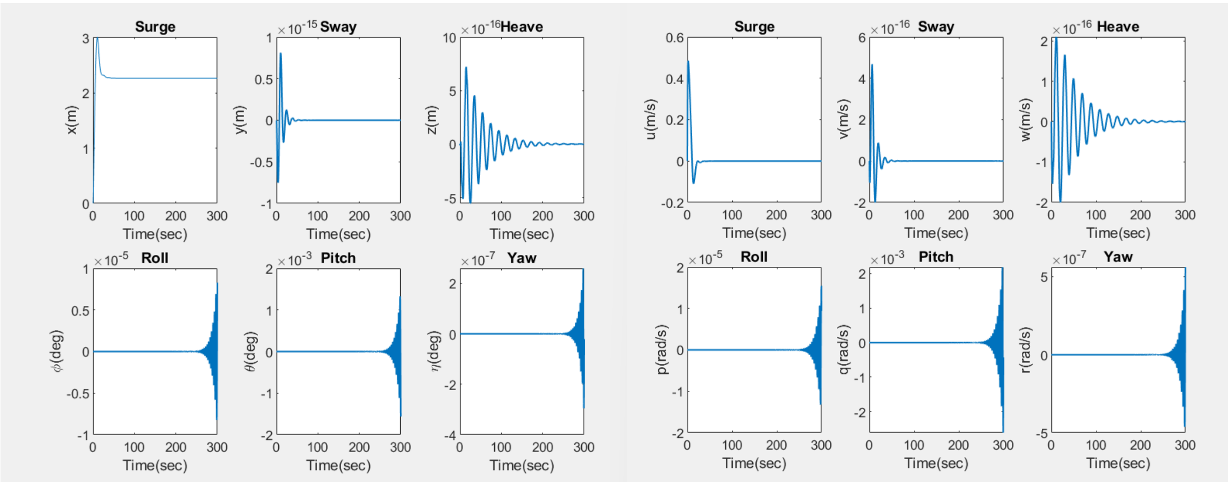

Fig. 10: Shows the position and velocity responses of Surge Forward motion in a closed loop system (Using PID controller, Kp=4, Ki=0.5 and Kd= 6) with 50% thrust values.

From figure 10, the simulations it is observed that the optimal stabilization is obtained through closed loop system with the PID controller with respect to the navigation of the ORCA in the desired direction of movement controlled by the pilot. Similar analysis was performed for all the other sway, heave, roll, yaw and pitch and almost the same results were observed. Hence it is proved and validated that the PID controller closed loop system performs best in for the navigation of the underwater ROV.

V. CONCLUSION

This study presents an analysis of the open loop and closed loop system for an indigenously developed low-cost ROV for inspection applications. The effect of various controllers on the velocity and position responses of ORCA is studied. The different response analysis of an open loop system suggests that, with 50% thrust to the respective thrusters in order to obtain a specified direction of motion, the ROV movement is observed in other directions too. After incorporating the controllers in the system, the analysis shows that these control systems improve the navigation of the ROV and minimize the changes caused by the external forces in underwater. In additional, a comparison has been performed among P, PI and PID controllers. The PID Controller was found to be optimal and has been successfully implemented in ORCA with feedback from the IMU (Inertial Measurement Unit) about its current position and hence reduce the error and obtains a stabilized navigation.

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