Control of Autonomous Underwater Vehicle (AUV) by comparison between different control techniques

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***Abstract*— The applications of various controllers like proportional, PID, PDA and fractional order PID controllers in the depth and motion control of AUV are being discussed with the help of two transaction papers named "AUV Buoyancy Control with Hard and Soft Actuators" and "Fractional-Order PID Motion Control for AUV Using Cloud-Model-Based Quantum Genetic Algorithm".**

In the first paper, the depth control of AUV is being discussed. The vertical motion or heave motion of AUV is achieved with the help of hard actuators (HA). But depth control using HA is highly expensive. So, by combining HA and SA AUVs can be stabilized at desired depth with minimum energy consumption. Simulations show that SAs and HAs in collaboration can reject large disturbances. A proportional controller is used for the control of HAs and Proportional derivative acceleration feedback controller is used for control of SAs.

In the second paper, the motion control of AUV is being discussed. In order to control the motion of AUV PID controllers can be employed. But instead of using PID control, fractional order PID controllers can be used to improve the performance of motion control. This superior performance of FPID over normal PID is verified with the help of simulations and experiments. For tuning the coefficients of FPID a cloud model-based quantum genetic algorithm is being discussed in this paper. With the help of super computers, it can be proved that genetic algorithm is more efficient to find optimal coefficients of FPID than random algorithm.

I. INTRODUCTION

Autonomous underwater vehicles (AUVs) are becoming popular due to their variety of underwater applications. AUVs operate independently of humans and have no physical connection to their operator. It can carry a variety of equipment like cameras, sonar and different other sensors for surveying and research purposes. The size of an AUV ranges from a few hundred pounds to several thousand pounds. The most attractive feature of AUV is that it can reach most of shallower water than boats can and deeper water than human divers or many tethered vehicles can. Some of the major application of AUVs are to obtain a map of the ocean floor, to identify hazards to navigation, to sense the waste materials left behind by humans, etc. In order to control the depth of an AUV, hard actuators can be used. But depth control using HAs alone will be very much expensive. So, by combining HA s and SAs the AUVs can be stabilized at desired depth with minimum energy consumption. The HAs are used to reach any desired depth at a less time, while SAs generate volume change to adjust the system's buoyancy to maintain neutral buoyancy at the desired depth. In the neutral buoyancy state, the HAs shut off while the SAs stabilize and maintain the depth with virtually zero energy consumption. The HAs use a proportional controller with a dead-band, while the SAs use a proportional-derivative-acceleration (PDA) feedback controller. Simulation results show that SAs alone can reject small disturbances while using both SAs and HAs in collaboration can reject large disturbances. Simulation results demonstrate that combining traditional HAs with SAs leads to dynamic performance and very low energy consumption capabilities that cannot be achieved by either one alone. Motion control systems for AUV have become very challenging due to strong coupling, high non-linearity and external disturbances. A variety of control systems are available, such as PID control, sliding mode control, H control and adaptive control. Nevertheless, the PID (proportional integral derivative) control is still the most widely used in AUV because of the simplicity and reliability. The fractional-order PID is a more generalized form for the conventional integer-order PID controller. It is represented by: $PI^{\lambda}D^{\mu}$ where λ and μ are the orders of the integrator and differentiator, respectively. For tuning the five parameters (Kp, Kd, Ki, λ, μ) many optimization methods are being used. Some of them are genetic algorithms (GA), particle swarm optimization (PSO) and gravitational search algorithm. Here cloud-model-based quantum genetic algorithm (CQGA) is being discussed.

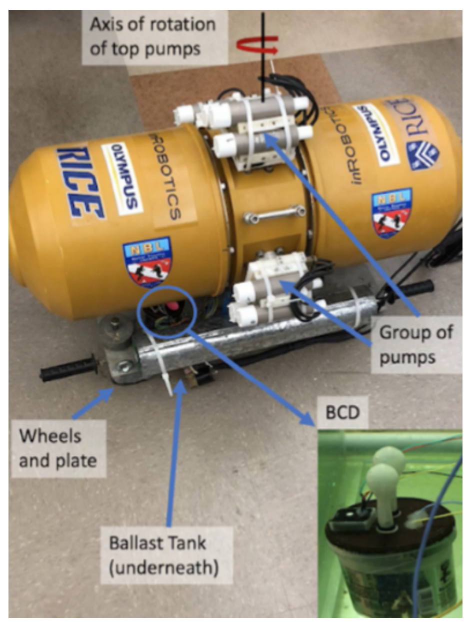

Fig. 1. The AUV with in-line pump HA thrusters and SA BCDs.

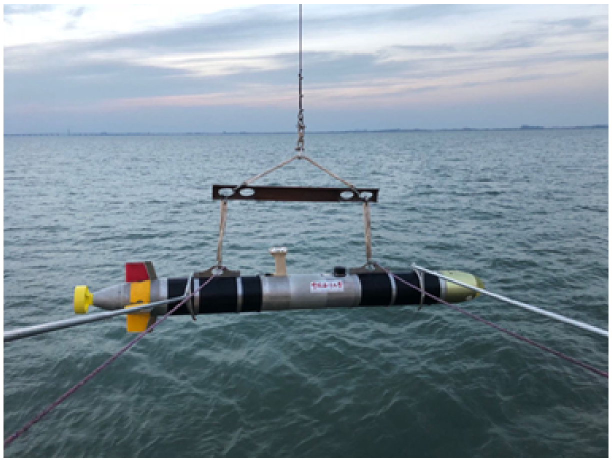

Fig. 2. Photo of AUV Sailfish.

II. Dynamics of AUV Model

The Dynamic equation of AUV is given as:

$$E\dot{U} = F_{vis} + F_{else}$$

Where F_{vis} is the hydrodynamic force with respected to an AUV moving in fluid, F_{else} is the external force such as the rudder force, propulsion force, gravity and buoyancy and E is given by:

$$E = \begin{bmatrix} m - X_{\dot{u}} & 0 & 0 & 0 & mz_G & 0 \\ 0 & m - Y_{\dot{v}} & 0 & -mz_G - Y_{\dot{p}} & 0 & -Y_{\dot{r}} \\ 0 & 0 & m - Z_{\dot{w}} & 0 & -Z_{\dot{q}} & 0 \\ 0 & -mz_G - Y_{\dot{p}} & 0 & I_x - K_{\dot{p}} & 0 & -K_{\dot{r}} \\ mz_G & 0 & -Z_{\dot{q}} & 0 & I_y - M_{\dot{q}} & 0 \\ 0 & -Y_{\dot{r}} & 0 & -K_{\dot{r}} & 0 & I_z - N_{\dot{r}} \end{bmatrix}$$

x_G, y_G, z_G : position of center of gravity for AUV;
x_B, y_B, z_B : position of center of buoyancy for AUV;
I_x, I_y, I_z : moments of inertia about x, y, and z axes;
$X_{\dot{u}}, Y_{\dot{v}}, Y_{\dot{r}}, Z_{\dot{w}}, Z_{\dot{q}}, K_{\dot{p}}, K_{\dot{r}}, M_{\dot{q}}, N_{\dot{v}}, N_{\dot{r}}$: hydrodynamic coefficients;
$U = [u, v, w, p, q, r]^T$: velocity (angular velocity) of six degrees of freedom;
$\dot{U} = [\dot{u}, \dot{v}, \dot{w}, \dot{p}, \dot{q}, \dot{r}]^T$: acceleration (angular acceleration) of six degrees of freedom;

The equation of components of hydrodynamic force F_{vis} is given by:

$$F_{vis} = [X_{vis}, Y_{vis}, Z_{vis}, K_{vis}, M_{vis}, N_{vis}]^T$$

The speed of AUV influenced by ocean current which is assumed to be a constant in time, uniform in space, and irrotational with respect to the world-fixed coordinate system, hence the relative velocity and acceleration of AUV is given by:

$$U = [u + u_r, v + v_r, w + w_r, p, q, r]$$

$$\dot{U} = [\dot{u} + \dot{u_r}, \dot{v} + \dot{v_r}, \dot{w} + \dot{w_r}, \dot{p}, \dot{q}, \dot{r}]$$

Where,

$$\begin{aligned} u_r &= u - U_c c\theta c(\alpha_c - \psi) \\ v_r &= v - U_c s\theta \\ w_r &= w - U_c s\theta c(\alpha_c - \psi) \end{aligned}$$

$$\begin{aligned} \dot{u_r} &= \dot{u} + U_c q s\theta c(\alpha_c - \psi) - U_c r c\theta s(\alpha_c - \psi) \\ \dot{v_r} &= \dot{v} - U_c s(\alpha_c - \psi) \\ \dot{w_r} &= \dot{w} + U_c q c\theta c(\alpha_c - \psi) - U_c r s\theta s(\alpha_c - \psi) \end{aligned}$$

U_c is the ocean current velocity of an irrotational fluid, and α_c is the angle of ocean current.
The gravitational matrix is given by

$$G = [0\,0\,0\ -hWc\phi s\phi\ -hWs\theta\ 0]^T$$

In order to analyze manipulating motion, the equation of motion can be divided into two non-interacting subsystems, the horizontal subsystem and the vertical subsystem. The following assumptions will be applied to the dynamic model: the AUV only moves at a low speed and the center of gravity is in the origin of the body-fixed coordinate system.

A. EQUATION OF MOTION IN THE HORIZONTAL PLANE:

Neglecting the elements corresponding to heave, roll and pitch, the horizontal equation of motion is generalized in:

$$\begin{aligned} m(\dot{u} – vr) &= X \\ m(\dot{v} + ur) &= Y \\ I_z\dot{r} &= N \end{aligned}$$

The X equation can be eliminated due to the fact that cruise speed u is a constant and $\dot{u}$ is zero. The fore and aft of AUV are asymmetrical, therefore the linearized maneuvering equation can be written as:

$$\begin{aligned} (m – Y_{\dot{v}})\dot{v} – Y_v v + Y_{\dot{r}}\dot{r} + (mu – Y_r)r &= Y_{\delta_r}\delta_r \\ (I_z - N_{\dot{r}})\dot{r} – N_r r + N_{\dot{v}}\dot{v} - N_v v &= N_{\delta_r}\delta_r \end{aligned}$$

As a result of starboard-port symmetry of AUV, $Y_{\dot{r}}$ and $N_{\dot{v}}$ are zero and eliminating v and ignoring the element corresponding to roll finally yields:

$$B_2\ddot{r} + B_1\dot{r} + B_0 r = A_1\dot{\delta_r} + A_0\delta_r$$

A1, A0, B2, B1 and B0 are presented in:

$$\begin{aligned} A_1 &= (m – Y_{\dot{v}})N_{\delta_r} \\ A_0 &= Y_{\delta_r}N_v – N_{\delta_r}Y_v \end{aligned}$$

$$\begin{aligned} B_2 &= (I_z – N_{\dot{r}})(m – Yv) \\ B_1 &= -Y_v(I_z – N_{\dot{r}}) – N_r(m – Y_{\dot{v}}) \\ B_0 &= N_v(mV – Y_r) + Y_v N_r \end{aligned}$$

After applying the Laplace's transformation, we get :

$$G_1(s) = \frac{r}{\delta_r}(s) = \frac{A_1 s + A_0}{B_2 s^2 + B_1 s + B_0}$$

$$G_2(s) = \frac{\psi}{\delta_r}(s) = \frac{A_1 s + A_0}{B_2 s^3 + B_1 s^2 + B_0 s}$$

substituting the hydrodynamic coefficients into the transfer function we get:

$$G_2(s) = \frac{1.9s + 2.8}{s^3 + 4.5s^2 + 4.4s}$$

B. EQUATION OF MOTION IN THE VERTICAL PLANE:

Neglecting the elements corresponding to sway, roll and yaw, the vertical equation of motion are given by

$$\begin{aligned} m\dot{u} &= X \\ m(\dot{w} + u_0 q) &= Z \\ I_y \dot{q} &= M \end{aligned}$$

The X equation can be eliminated due to the fact that cruise speed u is a constant and $\dot{u}$ is zero. The top and bottom of AUV are asymmetrical, therefore the linearized maneuvering equation can be written in:

$$(m - Z_{\dot{w}})\dot{w} – Z_w w + Z_{\dot{q}}\dot{q} + (mu + Z_q)q = Z_0 + Z_{\delta_s}\delta_s$$

$$(I_y – M_{\dot{q}})\dot{q} – M_q q – M_{\dot{w}}\dot{w} – M_w w = M_0 + M_{\delta_s}\delta_s + M_\theta \theta$$

As a consequence of starboard-port symmetry of AUV, $Z_{\dot{q}}$ and $M_{\dot{w}}$ are zero and eliminating $w, \dot{w}, q, \dot{q}$ and ignoring the element corresponding to roll finally yields

$$D_3 \dddot{\theta} + D_2\theta + D_1\dot{\theta} + D_0 = C_1\dot{\delta}_s + C_0\delta_s$$

C1, C0, D3, D2, D1 and D0 are presented in:

$$\begin{aligned} C_1 &= (m - Z_{\dot{w}})M_{\delta_s} \\ C_0 &= (Z_{\delta_s} M_w – Z_w M_{\delta_s})M_w \\ D_3 &= (I_y – M_{\dot{q}})(m – Z_{\dot{w}}) \\ D_2 &= -M_{\dot{q}}(m – Z_{\dot{w}}) – (I_y – M_{\dot{q}})Z_w \\ D_1 &= M_q Z_w – M_\theta(m – Z_{\dot{w}}) – M_w(mu + Z_q) \\ D_0 &= M_\theta Z_w \end{aligned}$$

After applying the Laplace's transformation, we get:

$$G_3(s) = \frac{\theta}{\delta_s}(s) = \frac{C_1 s + C_0}{D_3 s^3 + D_2 s^2 + D_1 s + D_0}$$

substituting the hydrodynamic coefficients into the transfer function we get:

$$G_3(s) = \frac{1.6s + 1.8}{s^3 + 4.5s^2 + 6s + 0.5}$$

III. CONTROLLER

A. FRACTIONAL-ORDER PID CONTROLLER

A fractional-order PID controller is described in time domain as:

$$u(t) = K_p e(t) + K_i \mathscr{D}^{-\lambda} e(t) + K_d \mathscr{D}^{\mu} e(t)$$

The frequency domain description of fractional-order PID controller is given by:

$$C(s) = K_p + K_i s^{-\lambda} + K_d s^{\mu}$$

where K_p is the proportional gain, K_i the integral gain and K_d the differential gain, λ and μ are the order of integral and differential controller, such that $\lambda, \mu \in (0, 1)$ respectively.

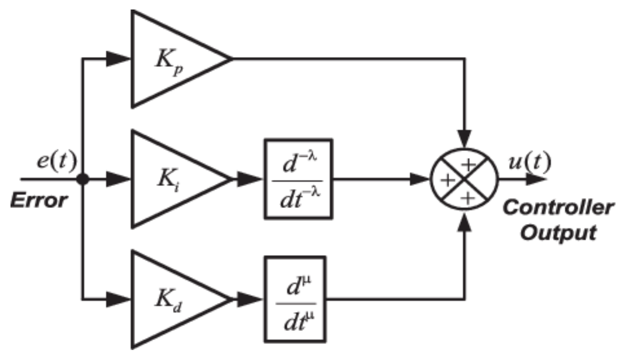

Fig. 3. Fractional Order PID controller

B. PID Controller:

PID controller is described in time domain as

$$u(t) = K_P e(t) + K_D \dot{e}(t) + K_i \int e(t)$$

Description of PID controller in frequency domain is given as

$$C(s) = K_p + K_d s + \frac{K_i}{s}$$

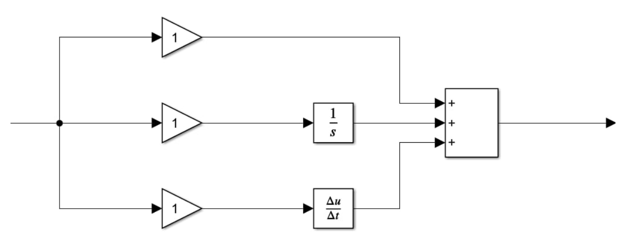

Fig. 4. PID controller

C. PDA Controller:

PDA controller is described in time domain as

$$u(t) = K_P e(t) + K_D \dot{e}(t) + K_A \ddot{e}(t)$$

frequency domain description of fractional-order PDA controller is given as

The PDA controller ensures that the AUV will have zero velocity and acceleration at the desired depth.
In Frequency domain it is given as

$$C(s) = K_p + K_d s + K_a s^2$$

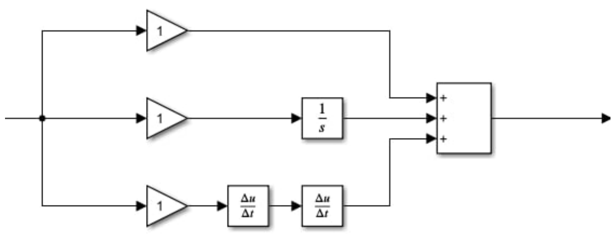

Fig. 5. PDA controller

IV. STABILITY

A. For PID Controller

In the integer-order system, it is well known from the theory of stability that all the roots of $Q(s) = 0$ have negative real parts. It means that they are located on the left half of the complex plane.

B. Fractional-order PID Controller

The stability of fractional-order system differs from the integer case. It is interesting that a stable fractional system may have roots in the right half of complex plane. The stable region of fractional-order system is given by Fig. 6

A commensurate-order system described by a rational transfer function is stable if and only if the following condition is satisfied

$$G(\gamma) = \frac{P(\gamma)}{Q(\gamma)}$$
$$|arg(\gamma_i)| > \alpha\frac{\pi}{2}$$

Where, $\gamma = s^\alpha$ and γ_i is the root of $Q(\gamma)$.

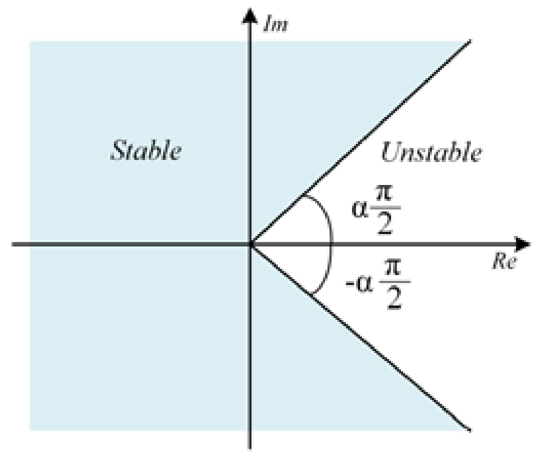

Fig. 6. Stable region of fractional-order systems with order $0 < \alpha < 1$

V. Hard and Soft Actuators

A. Hard actuators

Hard actuators include either the use of complex adjustable thrusters and propellers, design systems with larger bodies to incorporate control surfaces or at least one actuator for each DOF. And also, it is very difficult to achieve accurate depth control using purely HAs. These actuators use continuous firing which will results high power consumption. Since AUVs only carry limited power sources. These constraints lead to use the more precise and energy efficient control as Soft Actuators.

B. Soft Actuators

These are primarily used for adjusting system buoyancy. Buoyancy adjustments are achieved by varying the volume of fluid displaced via a compressed storage tank. There are so many methods to improve BCD dynamics. Incorporating buoyancy adjustment on AUVs as a means of depth control reduces the continual HA operation needed to maintain depth, saving energy. Nevertheless, the gas storage tank increases the overall volume of AUVs. By changing the volume of the gas it can adjust the buoyancy of AUV.

Initially, the HAs allow AUVs to reach the desired depth quickly while the SAs slowly take over and work to adjust buoyancy, gradually decreasing power usage. It is shown that the AUV achieves neutral buoyancy, and HAs been no longer required.

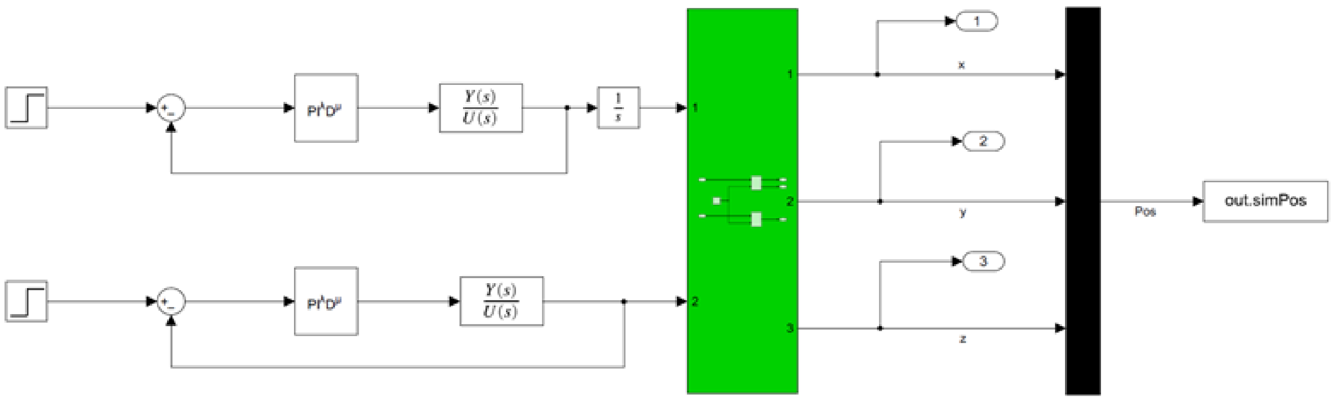

Fig. 7. Schematic of AUV

VI. Genetic Algorithm

Genetic Algorithms (GA) is global optimizing ones, based on natural selection and genetics mechanisms. They use a parallel procedure and structured strategy, but random, aiming to reinforce searching of high aptitude points. GA can be able to overcome complex non-linear optimization tasks like non-convex problems, non-continuous objective functions. GA consists of three fundamental operators: reproduction, crossover and mutation. Given an optimization problem, GA encode the parameters designed into finite bit strings, and then run iteratively using the three operators in random way but based on the fitness function evolution to perform the basic tasks of copying strings, exchanging portions of strings as well as changing some bits of strings, and finally find and decode the solutions to the problem from the last pool of mature strings.

Population unitization: This involves creating a population of N individuals. These are just DNA strands.
Fitness function calculation: This is where we understand from nature that survived of the fitness is a pretty good algorithm.
Cross over and mutation: the step of preparing for the next generation where the consequent participants are expected to be more fit than their parent generation

VII. Simulation

We have made this Simulink model using heading and pitch transfer functions given to us. Dynamics of AUV is simplified to a unicyclic model as we do not require the pos of unicycle while tracking its trajectory. The overview of the model is shown in the Fig. 7

We have also come across cloud-based quantum genetic algorithm but it required us to use quantum computer so we used genetic algorithm to tune our PID, FPID and PDA controllers. Also, we made a random value generating to compare our results from original genetic algorithm. Following are the step responses we got using both the above-mentioned algorithms.

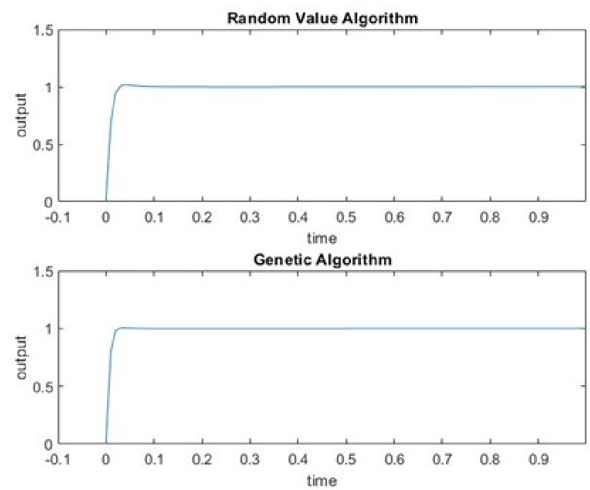

Fig. 8. Response of Random Value Algorithm Vs Genetic Algorithm

We have compared three control methods and calculated their responses as shown in Fig. 9

We have decoupled the motion of AUV into vertical and horizontal motion by using rudder and stern rudder as our actuators. Following figures shows the motion of AUV for vertical as well as horizontal planes and also in 3-D space.

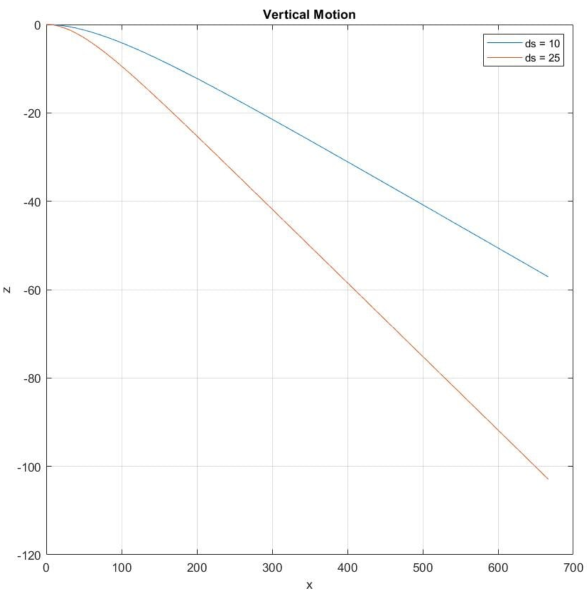

Fig. 9. Motion in Vertical Plane

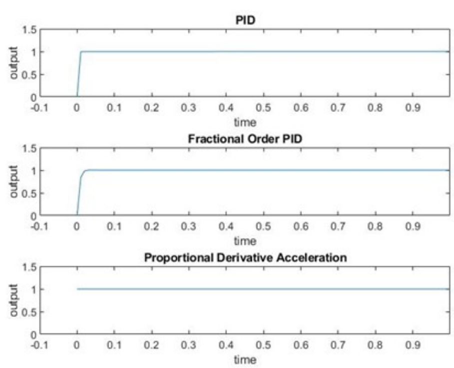

Fig. 10. Response of PID Vs Fractional Order PID Vs PDA Controller

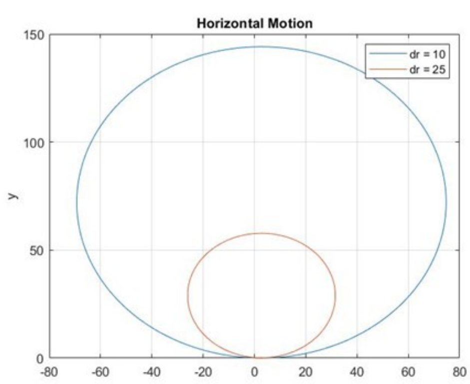

Fig. 11. Motion in Horizontal Plane

VIII. CONCLUSION AND RESULTS

In this paper, we compared fractional-order PID controller, PID controller and PDA controller using Genetic Algorithm and Random Value Algorithm. From results of several simulation, we found that in most of the cases Fractional-order PID controller performed better as compared to other controllers. We have decoupled the equations of motion into longitudinal and lateral motions and deduced transfer functions of heading and pitch which enabled us to make a very simple model of AUV. And also, we found Genetic Algorithm require a lot of computational power, but as quantum computing become popular then GA will be substituted by CQGA which will give faster and better results. As of now the methods like PSO (Particle swarm Optimization), Neural Networks, Fuzzy Networks are very popular for optimization problems. These methods can be used to improve the performance of AUV in future.

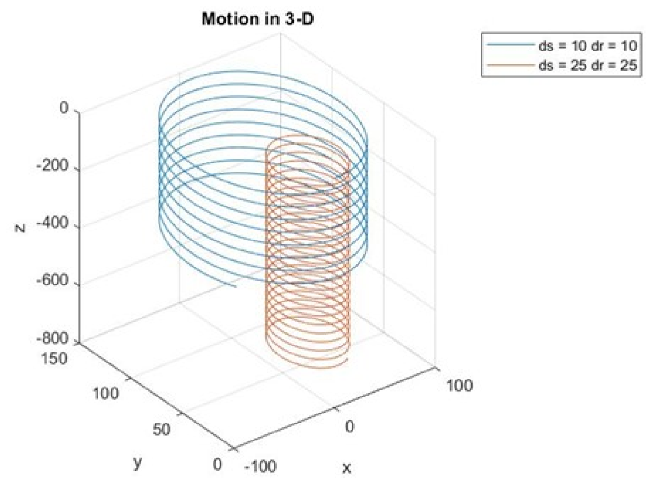

Fig. 12. Motion of AUV in 3-D plane

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