ISBN:978-93-82880-09-7

A simplified approach to tune PD controller for the depth control of an autonomous underwater vehicle

Sujay D. Kadam
Department of Instrumentation Engineering,
Shri Guru Gobind Singhji Institute
of Engineering and Technology,
Vishnupuri, Nanded, (MS), 431 606, INDIA.
Email: sujaykadam7@gmail.com

Kunal N. Tiwari
Department of Instrumentation Engineering,
Shri Guru Gobind Singhji Institute
of Engineering and Technology,
Vishnupuri, Nanded, (MS), 431 606, INDIA.
Email: kunal.n.tiwari@gmail.com

***Abstract*—The paper presents a simple method of tuning a PD controller for controlling the depth of an autonomous underwater vehicle. The non-linear dynamics of the depth of the vehicle are linearised and approximated as an integrating process with dead-time. The PD controller tuning is then done using gain margin specifications.**

***Keywords*—Autonomous Underwater Vehicle, Dead-time, integrating process, PD controller, tuning.**

I. Introduction

Autonomous underwater vehicle (AUV) is a robotic device use to carry out a variety of applications including survey of ocean floors, post-lay survey of pipelines, anti-submarine warfare or even as a tow device. The control of AUV has been area of interest for many researchers. The controlling of AUV is a challenging task partly due to the complex coupling in the subsystem [1] and partly due to the harsh and unpredictable environment in the ocean.

A varied number of techniques have been proposed for the depth control of AUV. A model of AUV with the three lightly interacting subsystem for steering, diving and speed control and autopilot design for the same was proposed by [2]. The possibility of AUV control by sliding mode controller was investigated by [3, 4] and the fuzzy sliding mode controller was proposed by [5]. Other intelligent controls include neural-networks [6] and single input fuzzy logic control [7]. The paper asserts the use of a simple PD controller for the depth control of the AUV making certain assumptions with the dynamics of the AUV.

II. Modeling of AUV

The modeling of AUV in 6 degree-of-freedom is done using two reference frames. The position and orientation of AUV are described with respect to earth fixed reference frame while the linear velocities (surge x, sway y and heave z) and angular velocities (roll p, pitch q and yaw r) are described with respect to body fixed reference frame. The velocity vector ν and position and orientation vector η can be represented as

$$\nu = [u, v, w, p, q, r,]^T \tag{1}$$
$$\eta = [x, y, z, \phi, \theta, \psi]^T \tag{2}$$

The mapping between the position and orientation and velocities is given by velocity transformation (also known as Euler angle transformation) and can be represented as:

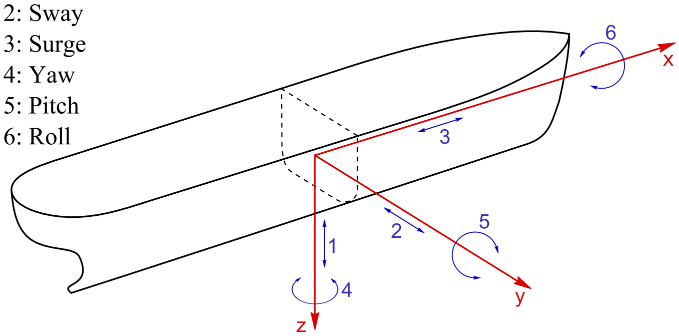

Fig. 1: The six degrees of freedom

$$\dot{\eta} = J(\eta)\nu \tag{3}$$

The nonlinear dynamics of AUV can be represented in a compact form as:

$$M\dot{\nu} + C(\nu)\nu + D(\nu)\nu + g(\eta) = \tau \tag{4}$$

Where,
$M\dot{\nu}$ is the 6×6 inertia matrix(including added mass)
$C(\nu)$ is the matrix of coriolis and centripetal terms (including added mass)
$D(\nu)$ is the damping matrix
$g(\eta)$ is the vector of gravitational forces and moments
τ is the vector of control inputs

The simplified equations of motion in pure depth plane can be written by assuming the origin of body fixed frame to coincide with center of gravity as:

$$m(\dot{w} - u_0 q) = \sum Z \tag{5}$$
$$I_{yy}\dot{q} = \sum M \tag{6}$$

The external forces and moments are expressed as :

$$\sum F_{ext} = F_{hydrostatic} + F_{lift} + F_{drag} + F_{control} + F_{disturbance} \quad (7)$$

The simplified version of above equation for the pure depth plane can be written as:

$$\sum Z = Z_{\dot{w}}\dot{w} + Z_{\dot{q}}\dot{q} + Z_w w + Z_q q + Z_{\delta_s}\delta_s \quad (8)$$

$$\sum M = M_{\dot{w}}\dot{w} + M_{\dot{q}}\dot{q} + M_w w + M_q q + M_\theta \theta + M_{\delta_s}\delta_s \quad (9)$$

For the vehicle in pure depth plane , we can assume the forward speed to be constant.Similarly we neglect sway and yaw modes ($\theta = constant\ and\ q_0 = \phi_0 = 0$). This gives

$$\dot{\theta} = q \quad (10)$$

$$\dot{z} = -u_0 sin\theta + w cos\theta$$

$$\therefore \dot{z} \approx -u_0\theta + w \quad (11)$$

Together the equation can be conveniently written in a matrix form as :

$$\begin{bmatrix} m - Z_{\dot{w}} & mx_g - z_{\dot{q}} & 0 & 0 \\ mx_g - M_{\dot{w}} & Iyy - M_{\dot{q}} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{w} \\ \dot{q} \\ \dot{\theta} \\ \dot{z} \end{bmatrix} \quad (12)$$

$$+ \begin{bmatrix} -Z_w & mu_0 + Z_q & 0 & 0 \\ M_w & mx_g u_0 - M_q & M_\theta & 0 \\ 0 & -1 & 0 & 0 \\ -1 & 0 & u_0 & 0 \end{bmatrix} \begin{bmatrix} w \\ q \\ \theta \\ z \end{bmatrix} = \begin{bmatrix} Z_{\delta_S} \\ M_{\delta_s} \\ 0 \\ 0 \end{bmatrix} \delta_s \quad (13)$$

The value of the dimensions, hydrodynamic coefficient and vehicle parameter are given in table (I). Using these values the equation can be written as:

$$\dot{x} = A(t)x + B(t)u \quad (14)$$

Where,

$$x = [w \quad q \quad \theta \quad z]^T$$

$$A = \begin{bmatrix} -0.6529 & -2.4522 & 0.0855 & 0 \\ 3.2219 & -3.1309 & -44.6794 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & -4.11 & 0 \end{bmatrix}$$

$$B = [0.4147 \quad -3.6757 \quad 0 \quad 0]^T$$

$$u = \delta_s$$

III. Depth Control of Autonomous Underwater Vehicle

The PD controller presented in has been applied for the control of autonomous underwater Vehicle in [7]. The depth of the AUV is controlled using the PD controller with disturbance observer as the depth dynamics of the AUV exhibit integrating process characteristics.

TABLE I: Parameters of AUV and their values

Parameter	Value
I_y	0.001925
m	0.036391
$M_{\dot{q}}$	-0.001573
$M_{\dot{w}}$	-0.000146
M_q	-0.01131
M_w	0.011175
M_θ	$0.156276/u_0^2$
M_δ	-0.012797
$Z_{\dot{q}}$	-0.000130
$Z_{\dot{w}}$	-0.031545
Z_q	-0.017455
Z_w	-0.043938
Z_δ	0.027695

A. Model of the AUV

The state-space model of the AUV is given by equation (14), which is a coupled system. The transfer function between depth (z) and stern plane displacement (δ_s) is obtained as,

$$\frac{Z(s)}{\Delta_s(s)} = \frac{1.4147s^2 + 25.4301s + 22.5863}{s^4 + 3.7838s^3 + 54.634s^2 + 28.8957s} \quad (15)$$

which can be represented as,

$$\frac{Z(s)}{\Delta_s(s)} = \frac{K}{s}G(s) \quad (16)$$

Where, $G(s)$ is the non-integrating part of the above transfer function given in equation (15).

$$G(s) = \frac{0.9623s^2 + 17.299s + 15.3648}{s^3 + 3.7838s^2 + 54.634s + 28.8957} \quad (17)$$

and $K = 1.47$, is the steady state gain of the overall transfer function. Since $G(s)$ is of a sufficiently high order, we can assume $G(s)$ to contribute some time lag (dead-time) i.e. $G(s) = G_p(s)e^{-ds}$. We can thus represent equation (16) as,

$$\frac{Z(s)}{\Delta_s(s)} = G_p(s)\frac{K}{s}e^{-ds}$$

We will ignore the dynamics contributed by $G_p(s)$ as pole at origin is very much dominant to any of the other poles of the transfer function given by equation (15).

B. Approximation of AUV depth transfer function as IPDT process

Approximation of the transfer function given by equation (15) has been done as shown in Fig. (2). The integrating part of the non-linear depth dynamics has been approximated as an integrator with gain K after a dead-time of d. The approximation of the open loop response of the depth transfer function gives the following IPDT process:

$$G_{AUV_{depth}}(s) = \frac{1.47}{s}e^{-0.5s} \quad (18)$$

i.e. $K = 1.47$ and $d = 0.5$.

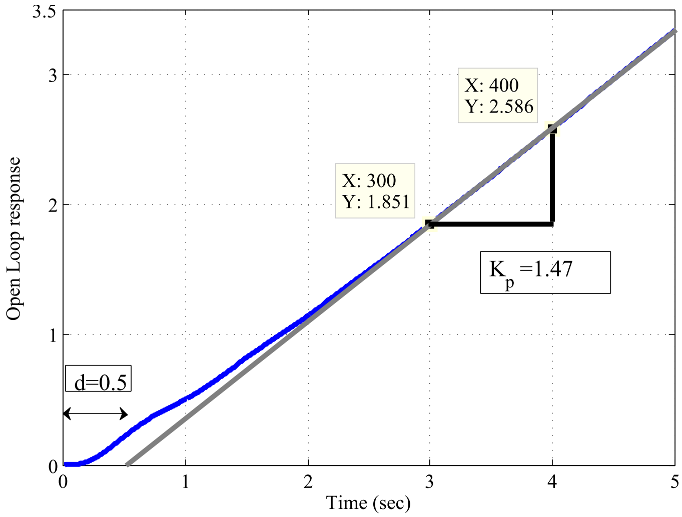

Fig. 2: Approximation of AUV depth transfer function as IPDT process

C. PD Controller settings

The PD controller of parallel form is considered for the depth control of the autonomous underwater vehicle approximated by equation (18). The depth dynamics being of integrating nature, integral mode is avoided. The parallel form PD controller transfer function is given by,

$$G_C(s) = K_P + K_D s \tag{19}$$

where, K_P and K_D are proportional and derivative gains respectively. The PD controller stated above is tuned by the tuning rules given by equations that follow.

$$K_D = \frac{d}{K} \tag{20}$$

$$K_P = \frac{d}{A_m\sqrt{1 + KK_D d}} \tag{21}$$

where, A_m is the desired gain margin.

The values for the PD controller gains for the approximated AUV depth transfer function are given in the table (II) below.

TABLE II: PD controller settings

A_m	K_P	K_D
1	0.4472	0.3401
2	0.2236	0.3401
3	0.1491	0.3401

IV. Simulations

The step response of the depth transfer function of the AUV is shown in Fig. (3). The effect of varying the gain margin specification as $A_m = 1, 2, 3$ is demonstrated in Fig. (4). With an increase in the value of gain margin specified, the response of the depth change becomes sluggish. The variations in Bode plots after using the controller settings for different gain margins ($A_m = 1, 2, 3$) are shown in the Figure. (5). The responses of the AUV to changes in depth command inputs is shown in Fig. (6).

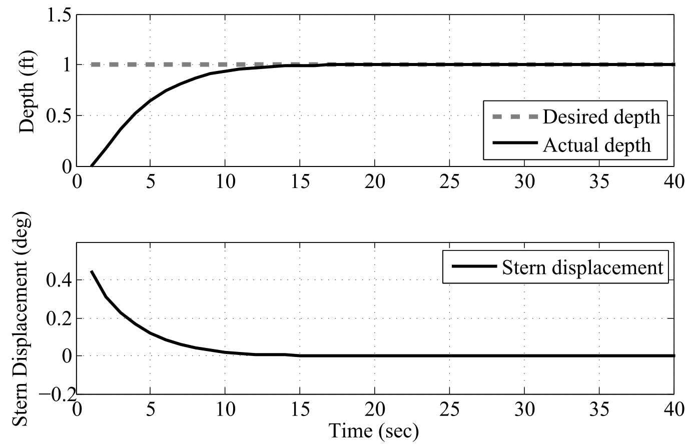

Fig. 3: Unit step response of the depth of AUV controlled by PD controller and the corresponding stern plane displacement

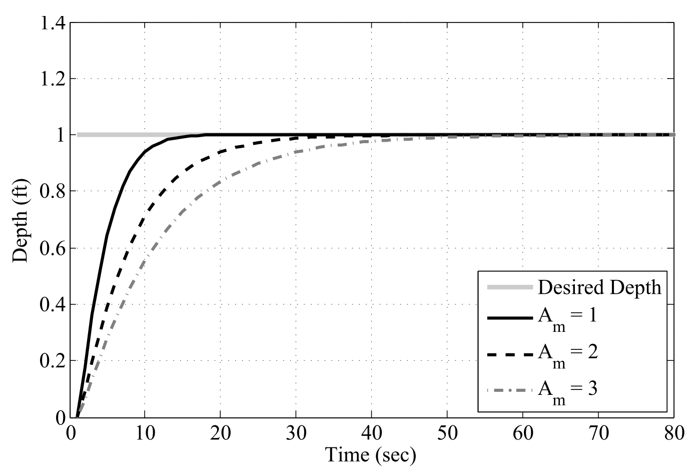

Fig. 4: Effect of varying the gain margin specification

The effect of depth tracking of the AUV on the heave velocity, pitch and pitch velocity is shown in Fig. (7).

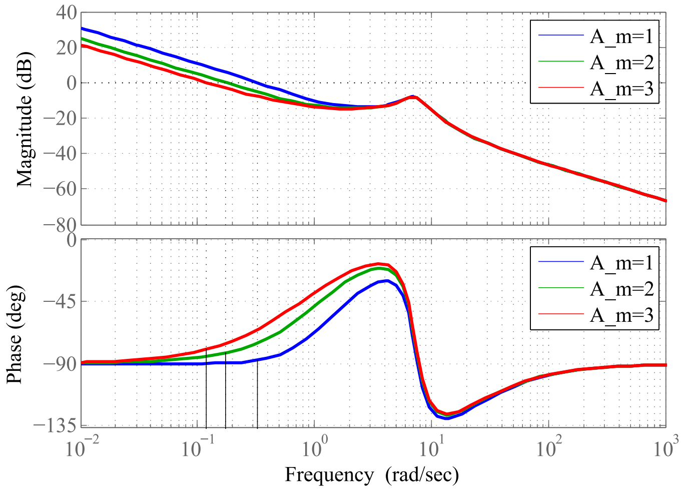

Fig. 5: Bode plots for different gain margin specifications

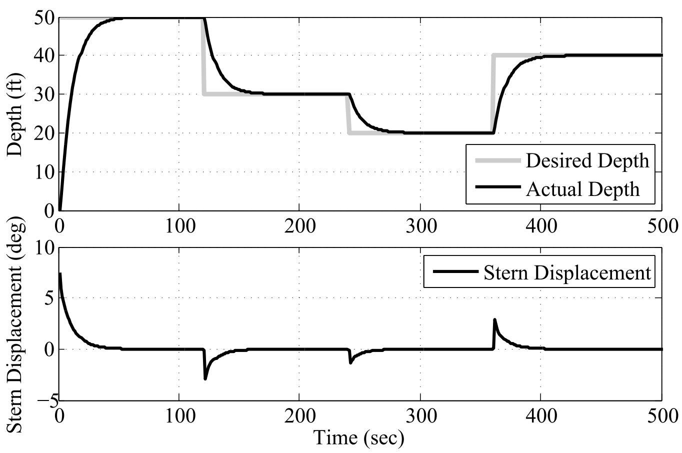

Fig. 6: Response of the AUV to change in depth and corresponding stern plane displacement

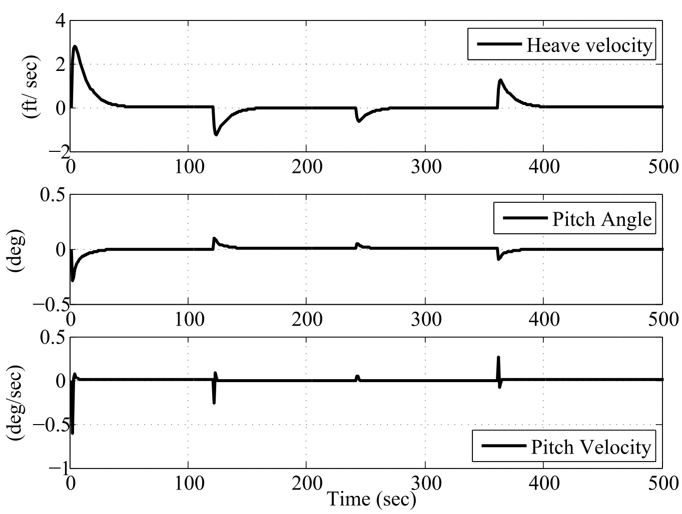

Fig. 7: Changes in heave velocity, pitch and pitch velocity with the change in the depth

V. Conclusion

The paper has presented the depth control of a autonomous underwater vehicle by approximating the non-linear dynamics of the vehicle as a process with integration using a simple PD controller. The simulations show that the PD controller performs acceptably with respect to the depth control without significantly affecting the values of pitch and heave velocities and the pitch angle. Also the stern plane displacement is smooth and achievable for a practical actuation system.

VI. Acknowledgements

This work is supported by Naval Research Board, Directorate of Naval Research and Development, DRDO under Project No. NRB-238/SC/11-12.

References

[1] K. Goheen and E. Jefferys, "The application of alternative modelling techniques to rov dynamics," in *Robotics and Automation Proceedings of IEEE International Conference on Robotics and Automation*, may 1990, pp. 1302 –1309 vol.2.

[2] B. Jalving and N. Storkersen, "The control system of an autonomous underwater vehicle," in *Proceedings of the Third IEEE Conference on Control Applications*, aug 1994, pp. 851 –856 vol.2.

[3] D. Yoerger, J.-J. Slotine, J. Newman, and H. Schempf, "Robust trajectory control of underwater vehicles," in *Proceedings of the 1985 4th International Symposium on Unmanned Untethered Submersible Technology*, vol. 4, jun 1985, pp. 184 – 197.

[4] T. I. Fossen and S. I. Sagatun, "Adaptive control of nonlinear systems: A case study of underwater robotic systems," *Journal of Robotic Systems*, vol. 8, no. 3, pp. 393–412, 1991. [Online]. Available: http://dx.doi.org/10.1002/rob.4620080307

[5] X. Shi, J. Zhou, X. Bian, and J. Li, "Fuzzy sliding-mode controller for the motion of autonomous underwater vehicle," in *IEEE International Conference on Mechatronics and Automation, ICMA*, aug. 2008, pp. 466 –470.

[6] S. Jagannathan and G. Galan, "One-layer neural-network controller with preprocessed inputs for autonomous underwater vehicles," *IEEE Transactions on Vehicular Technology*, vol. 52, no. 5, pp. 1342 – 1355, sept. 2003.

[7] K. Ishaque, S. Abdullah, S. Ayob, and Z. Salam, "A simplified approach to design fuzzy logic controller for an underwater vehicle," *Ocean Engineering*, vol. 38, no. 1, pp. 271 – 284, 2011. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0029801810002416