Velocity tracking and Pitch Depth Regulation of Biomimetic Autonomous Underwater Vehicle using Different Control Strategies

Aruna M V (arunodayam92@gmail.com)
IIT Madras: Indian Institute of Technology Madras

Research Article

Keywords: Control applications, Autonomous system, PID control

Posted Date: May 17th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1446676/v1

Velocity tracking and Pitch Depth Regulation of Biomimetic Autonomous Underwater Vehicle using Different Control Strategies

Aruna M V[1]

[1]Department of Ocean Engineering, Indian Institute of Technology, Madras, Adayar, Chennai, 600036, Tamilnadu, India.

Contributing authors: arunodayam92@gmail.com;

Abstract

Pertaining to the past twenty years, research on the movement control of Autonomous Underwater Vehicles (AUVs) has become a significant point because of their wide scope of utilization in different fields like environmental research, security patrol, surveillance, rescue, etc. In this paper, velocity tracking problem of a new Bio-mimetic (Biologically inspired) AUV in a horizontal plane and depth-pitch tracking is addressed. Bio-mimetic AUVs (BAUVs) strives to enhance performance in diverse ocean conditions. The performance parameters like speed, efficiency, maneuverability, and stealth are remarkable compared to conventional AUVs. The proposed modeling approach is based on the kinematics and dynamic equations of marine vehicles. A conventional Proportional-Integral-Derivative (PID) controller with different tuning methods is used in this work for motion controlling purposes. Later on, a robust control method is presented to achieve better performance.

Keywords: Control applications, Autonomous system, PID control

1 Introduction

Autonomous Underwater Vehicle (AUV) systems are fundamental in different parts of ecological examination. AUVs have an expansive range of sea life science applications and are likewise utilized in the academic, defense, illicit, and industrial sectors. These vehicles have revolutionized our ability to view the sea-floor, providing higher-resolution sea-floor mapping data than can be accomplished by surface vessels, especially in deep water [1].

The term bio-mimetic represents intimation of nature's method, mechanism, and processes into human-made systems. In recent years, researchers have been more focused on the efficient swimming capability of a fish and the potential benefits that can be applied to the design of marine vessels by imitating the bio-based swimming. Bio-mimetic AUVs are more efficient and maneuverable than other conventional underwater vehicles. A marine craft experiences the motion of 6 degrees of freedom (DOF) in maneuvering. The horizontal plane movements are alluded to as surge (longitudinal motion, typically superimposed on steady propulsive motion) and sway (side to side motion). Yaw (rotation of the vertical axis) defines the direction of the vessel. The remaining three DOFs are roll (longitudinal axis rotation), pitch (transverse axis rotation), and heave (vertical motion) [2].

Perilous and unknown surroundings, autonomy, and control of the vehicle are the key to the success of a mission. An intelligent control system is needed for developing motion control algorithms of the AUVs. This includes linear as well as non-linear controllers, which should perform satisfactorily. The controllers such as PD, PID, PPD [3], Integral controller, SMC controllers (Sliding Mode Control) [4], predictive control, and Fuzzy Logic Control (FLC) [5] introduced in the area of velocity and depth control. These all controllers have several advantages and disadvantages. One of the most crucial disadvantages of PD, PID, PPD controllers is difficulty in selecting an appropriate tuning method. SMC is an older approach that works well for many systems, although it can cause chattering on actuators, waste energy, and induce fin faults [3]. Some combination control methods can reduce this chattering effect. Predictive controllers are shoeing acceptable performance [6] in many applications. Among all the control methods, FLC is widely used in industrial process because of its simple structure and cost-effective design. However, FLC with fixed scaling factors and fuzzy rules [7] may not give complete performance if the plant is highly nonlinear or has uncertainties. Moreover, it completely relies on the designer's ability to make fuzzy rules.

Statement of Contributions: The main contribution of this paper includes the design of a velocity tracking control for the horizontal motion of the proposed BAUV and its depth and pitch control. AUV possesses a Gertler geometric-shaped hull with a flapping foil tail and a pair of horizontally connected pectoral fins. NACA63-015A foil is selected for the system design, which can mimic a tuna fish caudal fin with high propulsive efficiency. The same foil is chosen for pectoral fin design also. A Proportional Integral controller with different tuning methods is utilized here in the presence and absence of sea current for speed control and Depth-pitch control. If the vehicle is subjected to a huge wave when it comes closer to the sea surface, the heavy pitching may break the vehicle hull or breach. Another case of pitch control is presented in this work which eliminates the pitching effect and thus avoids the breaking of vehicle body. In order to achieve better performance against uncertainties, an H_∞ controller is also designed in this work. As a comparison study of the performance of different controllers used in this research, parameters such as rise time, settling time, and peak overshoot are introduced. A comparison study of existing controllers in this area with the proposed ones is also included to check the advantages and drawbacks.

2 System Description

The proposed system consists of mainly three blocks: Caudal/tail fin model, AUV body/hull and a pair of pectoral fins. The caudal fin propulsion model consists of an actuator that transmit forces to the fin and also produces the necessary exertion to drive the AUV. Therefore, caudal fin is connected to the AUV hull. Fig. 1 shows the cascaded connection of caudal fin system - AUV hull and parallel connection of pectoral fins. The design of the virtual model of BAUV posses a basic axis symmetric

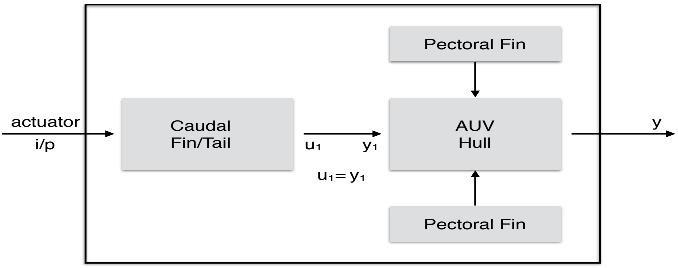


Fig. 1: Block diagram of Bio-mimetic AUV system

Gertler geometric shaped hull [8]. The proposed geometry of AUV hull is shown in Fig. 2. The profile is basic because it is possible to add modules at the mid-section for batteries or other equipment [8]. The process of adding such modules is known as Jumboising in Navel Architecture [8]. Fig 3 shows NACA63-015A foil, which used in this vehicle design. The Fig 4 illustrates the schematic model of Biomimetic

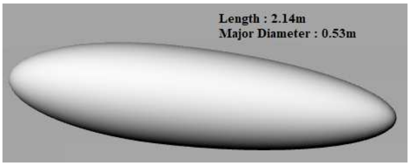


Fig. 2: Gertler Geometry

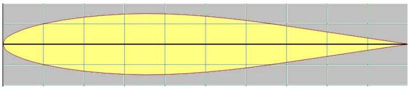


Fig. 3: NACA63-015A foil

AUV. The hull shape is inspired by the Ocean Explorer (OEx) of Florida Atlantic University [8], with a forward speed of 5 knots ($2.57m/s$). So this vehicle is also chosen the same operating speed.

2.1 Flapping foil/Caudal fin Depiction

It has been proved that, flapping foil fins can produce required thrust, so that the vehicle moves with higher maneuverability and speed [6]. Marine organisms overcome

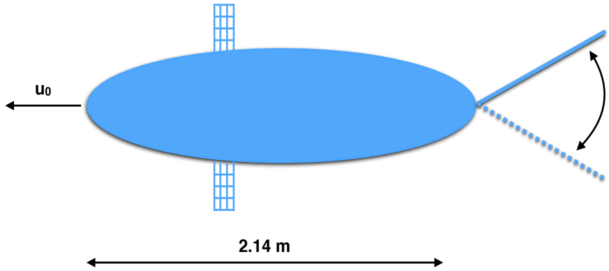


Fig. 4: Schematic model of Bio-mimetic AUV

the drag by producing thrust using its flapping fins. The caudal fin tail will undergo lateral and rotational motion, and motors are used to actuate the foil [6] system.
Performance Parameters: The study undertaken here to design a foil which can produce a maximum thrust of $\tau_X = 100N$. The flapping fin performance is evaluated by using it Strouhal number $(St = \frac{fA_0}{U_0})$ where f is the oscillation frequency of fin in Hz, A_0 is the double amplitude of fin oscillation and U_0 is the velocity [9] to the fin. The dimension parameters and frequency of the foil is illustrated in Table 1. The thrust

Table 1: Dimension parameters of the flapping foil

Flapping foil specifications	
Chord	0.16m
Breadth	0.2285m
Maximum thickness	0.03427m
Area	0.0757 m^2
Frequency	5.27 Hz

co-efficient is obtained as;

$$C_x = \frac{\tau_x}{0.5\rho U_0^2 A} \tag{1}$$

where A is the foil area and ρ is the water density. Similarly, average power coefficient (C_P) are also obtained from the analysis. It is defined as;

$$C_P = \frac{\tau_x}{0.5\rho U_0^3 A} \tag{2}$$

The efficiency of the flapping foil is defined as the ratio of output power to that of input power [9].

$$\eta = \frac{\tau_x.U}{P} = \frac{C_x}{C_P} \tag{3}$$

where P is the power required to oscillate the foil. All the performance parameters are described in Table 2.

Table 2: Performance parameters of the flapping foil

Strouhal Number (St)	0.31
C_X	0.40
Foil Drag	3.28 N
C_P	0.0376
Efficiency (%)	78.74

2.2 Pectoral fin depiction

The pectoral fin consists of a combination of heave and pitch motions, which narrates as:

$$\theta(t) = \theta_0 sin(\omega t + \psi) \tag{4}$$

$$h(t) = h_0 sin(\omega t) \tag{5}$$

where: θ_0 is the pitch amplitude, ψ is the phase angle between pitch and heave in radian and h_0 is the heave amplitude in meters. Value of ψ will be $pi/2$ in all experiments because hydrodynamic efficiency [10] is reported high for this. Therefore the pitch equation 4 will be,

$$\theta(t) = \theta_0 cos(\omega t) \tag{6}$$

The dimensional parameters and performance parameters of the pectoral fin are given in Table 3 and Table 5.

Table 3: Dimension parameters of the Pectoral fin

Pectoral fin specifications	
Chord	0.0718m
Breadth	0.0976m
Maximum thickness	0.01197m
Frequency	8 Hz

Table 4: Performance parameters of the Pectoral fin

Strouhal Number (St)	0.48
C_X	1.3209
Foil Drag	3.96 N
C_P	1.7586
Efficiency (%)	75.11

2.2.1 AUV hull dynamics

The proposed approach fixates the following dynamics equation [2] of the hull,

$$M\dot{v} + C(v) + D(v)v + g(\eta) = \tau \tag{7}$$

where, M is the Inertia matrix (added mass included), $C(v)$ is the Coriolis and centripetal matrix, $D(v)$ is the Damping matrix, $g(\eta)$ is vector of gravitational and buoyant forces and t represents Control input vector. An AUV possess 6 DOF motions and it is convenient to take the origin of body-fixed frame as the center of gravity of the vehicle. The reliability of the proposed control algorithm is verified using a 3 DOF underwater marine vehicle model [2]. The surge motion of AUV is considered for the velocity control of the vehicle in this work. From the dynamic equation (7) we get the 1-DOF system equation of surge velocity as,

$$(m - X_{\dot{u}})\,\dot{u} - X_u u = \tau_X, \tag{8}$$

where X_u denotes the rate of change of surge force per unit velocity u, and $X_{\dot{u}}$ denotes the added mass coefficient associated with acceleration $\dot{u}$. The term τ_X is the thrust generated at the x-direction. The initial aim of the work is to design a controller which gives a steady speed of $u_0 = 2.57m/s$ for the proposed Bio-mimetic AUV.

2.3 Caudal fin dynamics

The approach is inspired and borrowed by Lighthill [11]. Lighthill has modeled the fish tail, which produces lateral and rotational motions. The forces and moments produced by the foils are complicated, which is derived by using unsteady aerodynamic theory [12] [13]. The proposed system is a motor-driven oscillating foil system. Theodorsen [13] derived the expression for the moment and lift, which act on the foil at the constant velocity free-stream where the foil is harmonically oscillating. Let F and τ are the driving force and torque applied, and L and M are the hydrodynamic lift and moment acting on the foil, respectively. According to the unsteady aerodynamic theory [14], [12],

$$m(\ddot{Z} + \ddot{\alpha}b) = L + F_a \tag{9}$$

where Z is the vertical position and m is the mass.

$$J\ddot{\alpha} = M + \tau_a - F_a b \tag{10}$$

where α is the angular position (pitch angle), J is the moment of inertia and b is the position of axis of rotation along the chord. A complete derivation of lift and moment. A complete derivation of lift and moment has been done by Harper at al.[14] including added mass, wake effect, quasi-steady lift and moment, and thrust and drag based on unsteady aerodynamic theory [13]. Therefore;

$$L = 2\pi\rho a U(-\dot{Z} + U\alpha + (\frac{a}{2} - b)\alpha)C(i\omega) + \pi\rho a^2(-\ddot{Z} + U\dot{\alpha} - b\ddot{\alpha}) \tag{11}$$

$$M = -2\pi\rho a U(\frac{a}{2})^2\dot{\alpha} + \pi\rho a^2 U(-\dot{Z} + U\alpha + (\frac{a}{2} - b)\dot{\alpha})C(i\omega) - \frac{\pi}{8}\rho a^4\ddot{\alpha} \tag{12}$$

where ρ is density, a is half chord length of tail, U is free stream velocity and $C(i\omega)$ is Theodorsen function. A third order transfer function obtained for the good approximation of Theodorsen function [13], in this study is

$$C(i\omega) = \frac{a_3(i\sigma)^3 + a_2(i\sigma)^2 + a_1(i\sigma) + a_0}{(i\sigma)^3 + b_2(i\sigma)^2 + b_1(i\sigma) + b_0} \tag{13}$$

where $\sigma = \frac{\omega a}{U}$ which is a non dimensional reduced frequency. The equations (11), (12) substitutes in (9), (10) and forms state space representation of the caudal fin system. The inputs of the system are applied force (F_a), torque (τ_a) and the state vector is $x = \begin{bmatrix} Z & \alpha & \dot{Z} & \dot{\alpha} & x_f \end{bmatrix}^T$ where $x_f = \begin{bmatrix} x_{f1} & x_{f2} & x_{f3} \end{bmatrix}^T$. The state vector x_f corresponds to Theodorsen [13] function and the outputs from the caudal fin system are forward thrust and moment. All these parameters are explained in the system model Figure 5.

2.4 Pectoral fin dynamics

The hull with pectoral fin vehicle moving in x-z plane [15], and the coordinates of the center of gravity of the vehicle $[x_g, y_g, z_g] = [0.075, 0, 0]$. The heave and pitch equation of the neutrally buoyant vehicle with pectoral fin [15] is described below:

$$\begin{aligned} m[\dot{w} - uq - x_g\dot{q} - z_g q^2] &= Z_{\dot{q}}\dot{q} + Z_{\dot{w}}\dot{w} + Z_{uq}uq + Z_{uw}uw + F_p \\ I_y\dot{q} - m[x_g(\dot{w} - uq) - z_g wq] &= M_{\dot{q}}\dot{q} + M_{\dot{w}}\dot{w} + M_{uq}uq + M_p - x_{gb}W cos\theta - z_{gb}W sin\theta] \\ \dot{\theta} &= q \\ \dot{z} &= w - u\theta \end{aligned} \tag{14}$$

Here w is the heave velocity, θ is the pitch angle, F_p and M_p are the net force and moment produced by the pectoral fin. The forward velocity is kept constant by a control mechanism and for simplicity nonlinear coefficients are eliminated, then the system will be;

$$\begin{bmatrix} (m - Z_{\dot{w}}) & (mx_g - Z_{\dot{q}}) \\ (-mx_g - M_{\dot{w}}) & (I_y - M_{\dot{q}}) \end{bmatrix} \begin{bmatrix} \dot{w} \\ \dot{q} \end{bmatrix} = \begin{bmatrix} Z_w U & Z_q + mU \\ M_w U & M_q - mx_g U \end{bmatrix} \begin{bmatrix} w \\ q \end{bmatrix} + \begin{bmatrix} F_p \\ M_p \end{bmatrix} \tag{15}$$

Re-writing the equation (14),

$$\begin{aligned} \begin{bmatrix} \dot{w} \\ \dot{q} \end{bmatrix} = \begin{bmatrix} (m - Z_{\dot{w}}) & (mx_g - Z_{\dot{q}}) \\ (-mx_g - M_{\dot{w}}) & (I_y - M_{\dot{q}}) \end{bmatrix}^{-1} \begin{bmatrix} Z_w U & Z_q + mU \\ M_w U & M_q - mx_g U \end{bmatrix} \begin{bmatrix} w \\ q \end{bmatrix} + \\ \begin{bmatrix} (m - Z_{\dot{w}}) & (mx_g - Z_{\dot{q}}) \\ (-mx_g - M_{\dot{w}}) & (I_y - M_{\dot{q}}) \end{bmatrix}^{-1} \begin{bmatrix} F_p \\ M_p \end{bmatrix} \end{aligned} \tag{16}$$

This equation of the form of state space representation, $\dot{x} = Ax + Bu$ and the output equation will be,

$$y = \begin{bmatrix} 1 & 1 \end{bmatrix} \begin{bmatrix} w \\ q \end{bmatrix} \tag{17}$$

2.5 Representation of the System

The inputs given to the caudal fin are lateral and angular positions, from the motor actuator. Due to the motions of the fin it can produce the forward thrust ($\tau_X = 100N$) and the angular moment which are used as the input to the AUV hull subsystem. Caudal fin and hull subsystem are taken as a cascade connection, and the pectoral fin subsystem is connected parallel to this. The inputs to the pectoral fin are heave thrust and pitch moment where as output from this system are heave and pitch velocities. This system is subjected to the control applications such as velocity control and depth -pitch control. Figure 5 illustrated the MATLAB/Simulink model of the proposed system.

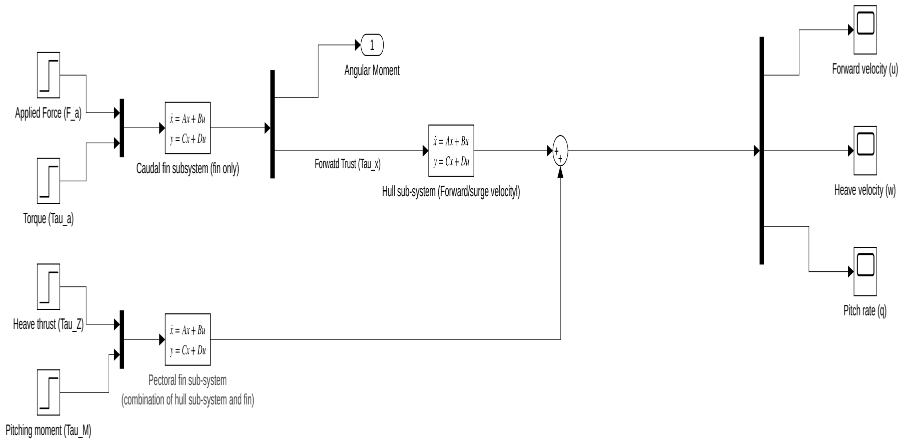


Fig. 5: Simulink model of the Biomimetic AUV system

2.6 Disturbance Effects

Two disturbance effects such as ocean current disturbance and wave disturbance are introduced in the analysis of the system.

Ocean current disturbance : Ocean current effects are horizontal and vertical circulation systems of ocean waters created by gravity, wind friction, and water density change in different areas of the ocean. Using Fossen's methodology in marine disturbance modeling, the equation of motion of ocean currents can be represented in in terms of relative velocity v_r [2], [16] as,

$$v_r = V - V_c \tag{18}$$

where $Vc = \begin{bmatrix} u_c & v_c & w_c & 0 & 0 & 0 \end{bmatrix}^\top$ is the ocean current velocity vector, considering that the current does not generate rotational movement on the vehicle.

Wave disturbance: In general AUV experiences only ocean current disturbances. As it approaches the surface of the sea, it experiences wave disturbance. The following Wave transfer function is considered in this work:

$$h(s) = \frac{K_\omega}{s^2 + 2\lambda\omega_0 s + \omega_0^2} \tag{19}$$

where λ is damping coefficient and ω_0 is dominating wave frequency, and $K_\omega = 2\lambda\omega_0\sigma$ with σ as the wave intensity. Here the wave is considering with following parameters such as;

Table 5: Disturbance wave parameters

Wave height	4.1 m
Wave length	77 m
ω_0	0.7302 rad/s
σ	1639.98 W/m^2

3 Controller Design

3.1 PID Controller based Velocity Tracking

Control of AUV is an intensely scrutinized subject, however, barely an open issue because of the natural aggravations, vehicle conduct, the intricacy of the vehicle hydrodynamics, etc. In many applications, velocity tracking control [17] is a key to most of the control problems of AUVs. PID controller-based system can track the desired surge velocity of the proposed AUV. The time domain output of a PID controller $y(t)$, is calculated from the feedback error denoted as $e(t)$ as follows:

$$y(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt} \tag{20}$$

where K_p, K_i and K_d are the controller gains.

3.1.1 PID controller Manual tuning

Manual tuning of PID controller is accomplished by by increasing the gain until the loop oscillates at a constant amplitude and setting the reset time to its maximum value and the rate to zero. The attained equation with gain values (20) with the presence and absence of ocean current disturbances are given as:

$$y(t) = 0.522e(t) + 0.511 \int e(t)dt + 0.1 \frac{de(t)}{dt} \tag{21}$$

$$y(t) = 1e(t) + 0.12 \int e(t)dt + 0.28 \frac{de(t)}{dt} \tag{22}$$

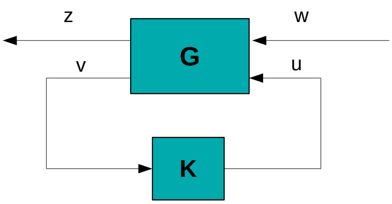


Fig. 6: General formulation of a robust control problem

3.1.2 PID controller Ziegler-Nichols tuning

This is a well known and popular method of PID tuning [18]. In this work, the obtained ZN tuning values with PID controller equation (20) is given by:

$$y(t) = 0.789e(t) + 0.161 \int e(t)dt + 0.516\frac{de(t)}{dt} \tag{23}$$

3.1.3 PID controller Genetic Algorithm tuning

A genetic algorithm (GA) is a heuristically designed evolutionary algorithm (EA) inspired by natural selection [19]. Here, the procured equation (20) with the presence and absence of ocean current disturbances using this method will be:

$$y(t) = 2e(t) + 0.83 \int e(t)dt + 2.45\frac{de(t)}{dt} \tag{24}$$

$$y(t) = 1.3798e(t) + 0.0951 \int e(t)dt + 3.4891\frac{de(t)}{dt} \tag{25}$$

3.2 Velocity tracking using H-infinity controller

H_∞ controller is a robust strategy and uses different methods for the formulation of H_∞ optimization problem. The mixed sensitivity approach is selected here that uses weighting function method to solve the control problem [20], [21]. The formulation of a robust control system is depicted in the Fig. 6 given below. In the figure $G(s)$ is the plant open-loop transfer function, and $K(s)$ is the controller transfer function, u is the control signal, v measured output, w exogenous inputs and z is the error variable. The main objective of this system is to find out the controller $K(s)$. The H_∞ controller synthesis employs two transfer functions S and T, in which one dealing with stability and other dealing with performance. The Sensitivity function, S and the Complementary sensitivity transfer function, T are given as; $S(s) = \frac{1}{1+GK}$ and $T(s) = \frac{GK}{1+GK}$. Now the objective is minimizing the infinite norm of the transfer function $T_{zw}(s)$, where

$$T_{zw}(s) = \begin{bmatrix} W_S(s)S(s) \\ W_T(s)T(s) \end{bmatrix} \tag{26}$$

The parameters W_S and W_T are the weights given by the designer.

3.2.1 Selection of Weighting Functions

$W_S(s)$ and $W_T(s)$ are the weighting matrices of Sensitivity transfer function and Complementary Sensitivity transfer function respectively. $W_S(s)$ is selected to reflect the desired performance characteristics. The sensitivity function should have low gain at low frequencies for good tracking performance and high gain at high frequencies to limit overshoot. Therefore select a weighting function $W_S(s)$ such that W_S^{-1}reflects the desired shape of the sensitivity function.

The response of the system to reference inputs and sensor noise inputs is given by the Complementary sensitivity function. Since noise has most of its energy concentrated at high frequencies, a high pass weight is used in the complementary sensitivity function [22]. This keeps the weighted complementary sensitivity function near unity at low frequencies and low at higher frequencies. The minimization of magnitude of S and T can be achieved by making $\mid S(j\omega) \mid < \frac{1}{W_S(j\omega)}$ and $\mid T(j\omega) \mid < \frac{1}{W_T(j\omega)}$. Another Method of limiting the controller bandwidth and providing high frequency gain attenuation is to use a high pass weight on an unmodified dynamics uncertainty block that may added from the plant input to the plant output. The characteristics of this weighting function $W_{KS}(s)$ are very similar to the complementary sensitivity weighting function. When using both sensitivity and complementary sensitivity transfer functions it is important to make sure that the magnitude of these weights at frequency where they cross is less than one. Also the weighting functions do not have any poles or zeros on the imaginary axis, which makes the system internally unstable. In most of the design methods weighting functions are selected using trial and error method [22]. A vital starting point, that being said, is to choose; $W_S(s) = \frac{s/M+\omega_0}{s+\omega_0 A}$, $W_{KS} = constant$ and $W_T(s) = \frac{s+\omega_0/M}{As+\omega_0}$ with A is the maximum allowed steady state offset, M is the sensitivity peak and ω_0 is the desired bandwidth.

In this study, the velocity plane dynamics of the vehicle considered is second order. So the weighing functions for velocity system is taken as $W_S = \frac{s}{12s+1.2}$, $W_T = \frac{s+5}{0.1s+10}$ in the absence of disturbance and the control signal weighing function W_{KS} is small in all the cases. Velocity system with the presence of disturbance case, $W_S = \frac{s}{20s+2}$ and $W_T = \frac{s+10}{0.2s+20}$. The depth plane dynamics of the proposed system is third order, in which the pitch itself is a second-order system. Thus the weighing functions W_S and W_T are designed as second-order low pass and high pass filters, respectively. The values are $W_S = \frac{51}{s^2+6s+2}$, $W_T = \frac{s^2+12s+9}{350}$. The weighting functions are chosen in such a way that there are no poles or zeros at the imaginary axis. Hence the system is internally stable. Algorithms are coded in `MATLAB` and the result are obtained.

3.3 Pitch Control System

Pitch is the rotation about the transverse axis, which is an up-down motion of the vehicle. Often, pitch motion is one of the main causes for surveillance video fuzziness. Accordingly, the pitch movement control is significant for the submerged vehicle execution. Here the main aim is to achieve zero vehicle pitching angle. Pitch system also used PID controller tuning methods and H_∞ controller for performance analysis. H_∞ controller design for the elimination of pitching effect is same as that of velocity tracking controller. PID controller output equations with gain values for different cases along distinct tuning methods are given below (20):

- **Case I:** Pitch system without any disturbance
  - PID controller with manual tuning

$$y(t) = 88e(t) + 1\int e(t)dt + 220\frac{de(t)}{dt} \tag{27}$$

  - PID controller with Genetic Algorithm tuning

$$y(t) = 96e(t) + 0.1751\int e(t)dt + 122\frac{de(t)}{dt} \tag{28}$$

- **Case II:** Pitch system subjected to wave disturbance
  - PID controller with manual tuning

$$y(t) = 64e(t) + 2.77\int e(t)dt + 211\frac{de(t)}{dt} \tag{29}$$

  - PID controller with Genetic Algorithm tuning

$$y(t) = 48.23e(t) + 1.75\int e(t)dt + 202\frac{de(t)}{dt} \tag{30}$$

3.4 Depth Tracking Control

In many scenarios, depth control is a crucial part of an AUV; for example, while mapping a seabed, an AUV have to maintain a constant distance from the seabed. Pitch control is an unavoidable part of depth tracking system. Figure. 7 describes the block diagram of a dual loop Depth-pitch controller with disturbance effect. The

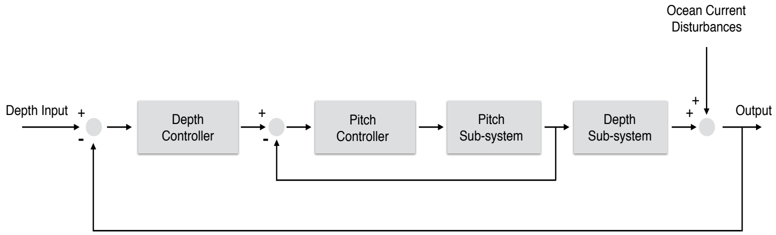


Fig. 7: Schematic of Depth control dual loop system with disturbance effect

intent of depth tracking controller design is to keep the vehicle at a particular depth, say $u = 40m$. In order to achieve this value (with and without ocean current disturbance effect), conventional PID controller is used first with different tuning methods. Then H_∞ controller is used to analyse the performance evaluation.

- **Case III:** Depth-Pitch dual loop system with the absence and presence of ocean current disturbance

- PID controller manual tuning without disturbance (outer loop depth system)

$$y(t) = 13.2e(t) + 50.2 \int e(t)dt + 0.776 \frac{de(t)}{dt} \tag{31}$$

- PID controller Genetic Algorithm tuning without disturbance (outer loop depth system)

$$y(t) = 0.325e(t) + 4.09 \int e(t)dt + 0.327 \frac{de(t)}{dt} \tag{32}$$

- PID controller manual tuning with disturbance (outer loop depth system)

$$y(t) = 250e(t) + 18 \int e(t)dt + 2.39 \frac{de(t)}{dt} \tag{33}$$

- PID controller Genetic Algorithm tuning with disturbance (outer loop depth system)

$$y(t) = 291.41e(t) + 10.19 \int e(t)dt + 3.39 \frac{de(t)}{dt} \tag{34}$$

4 Simulation Results

In this section, the simulation results of a velocity tracking control algorithm for AUVs moving in the horizontal plane and pitch-depth control system for various conditions are presented.

4.1 Velocity Tracking controller simulations

The control system is implemented based on the change of speed, which prompts identical movement conditions. The results obtained are shown the effectiveness of the velocity controller. The location of the closed loop pole of the system guarantees the stability and controllability of the system in presence of model uncertainties. Figure 8 shows the open-loop velocity response of the Biomimetic AUV system. A

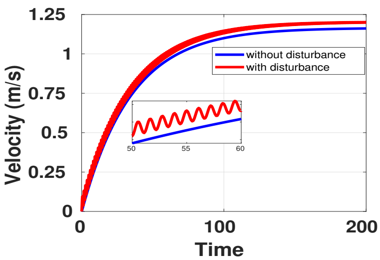
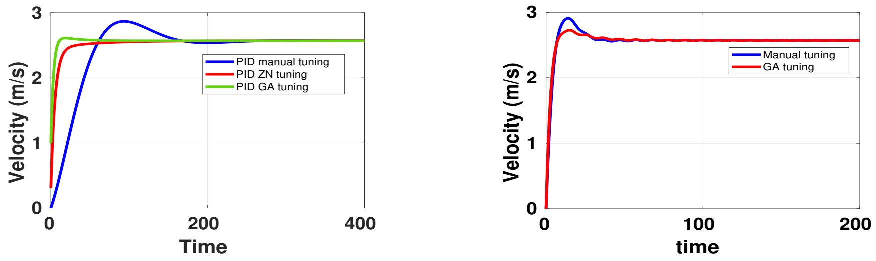


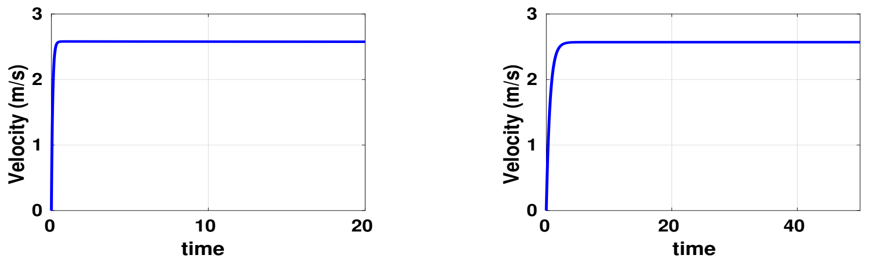
Fig. 8: Open-loop velocity response of the system

PID controller with different tuning methods such as manual tuning, Zieglar Nichols (ZN) tuning and Genetic Algorithm (GA) tuning are applied to the proposed system for the velocity control applications. Figure 9a shows the response of a velocity tracking system without disturbance using PID controller tuning algorithms and Figure 9b illustrates the velocity control system with the presence of ocean current disturbance. Figure 10a and 10b describes controlled response of surge velocity using H_∞ controller without and with the presence of ocean current disturbance. Table 6 compares performance parameters of the velocity tracking system with different tuning algorithms.



(a) without disturbance (b) with disturbance

Fig. 9: Closed-loop velocity response using PID controller



(a) without disturbance (b) with disturbance

Fig. 10: Closed-loop velocity response using H_∞ controller

Table 7 illustrates the comparison of performance PID controller manual tuning, Genetic Algorithm tuning, and H-infinity controller method. Its clear from Table 6 and 7 that the H_∞ controller giving better performance than the other controller with and without disturbance. The performance of the PID controller with genetic algorithm tuning gives better performance than using manual tuning.

4.2 Depth-pitch controller simulations

A dual-loop depth controller design with inner pitch controller and outer depth controller had been designed and accomplished.

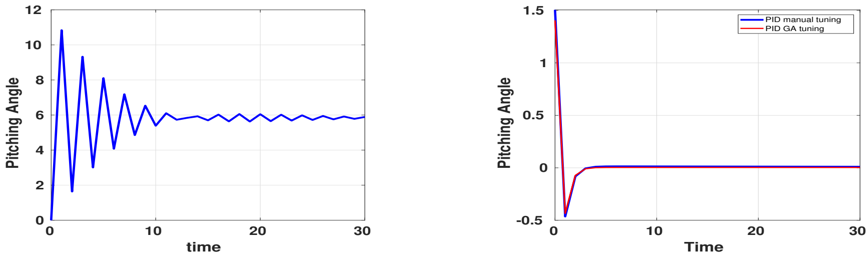
Table 6: Comparison of performance parameters of velocity tracking system without disturbance

Performance Parameters	PID controller tuning methods		
	Manual tuning	*ZN tuning*	*GA tuning*
Rise time (sec)	45.0290	14.1497	6.3452
Settling time (sec)	150.2918	50.3888	21.4140
Overshoot (%)	11.5970	2.0122	1.5866

Table 7: Comparison of performance parameters of velocity tracking system with disturbance

Performance Parameters	Controllers		
	PID controller Manual tuning	*PID controller GA tuning*	*H-infinity controller*
Rise time (sec)	63.1090	22.1581	3.4238
Settling time (sec)	91.8234	31.6581	5.5170
Overshoot (%)	4.6913	2.2012	1.1296

Case I: Only Pitch system is considered without any disturbance effect using different controllers illustrated in Figure 11a, 11b and Figure. 12.



(a) Open loop response without disturbance,

(b) Controlled response without disturbance,

Fig. 11: Pitching responses of the AUV system

Case II: Pitch system with wave disturbance is considered with the assumption that the vehicle is very close to the sea surface. The vehicle is subjected to a wave of Wave length 77m and Wave height of 2m. Simulation results are described in Figure 13a, 13b and 14.

Case III: Depth – pitch controller - Inner pitch controller and outer depth controller had been designed and implemented with and without Ocean current disturbance case when the vehicle is moving at a particular distance below from the sea surface.

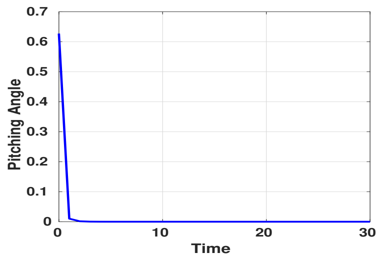
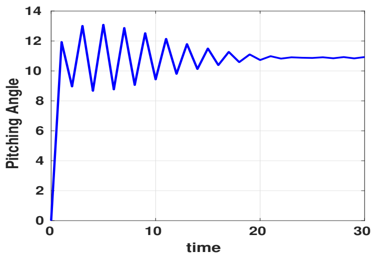
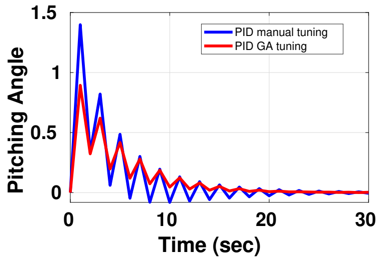


Fig. 12: Pitching responses of the AUV system using h_∞ controller (without disturbance)



(a) Open loop response,



(b) Controlled response,

Fig. 13: Pitching responses of the AUV system subjected to a wave disturbance

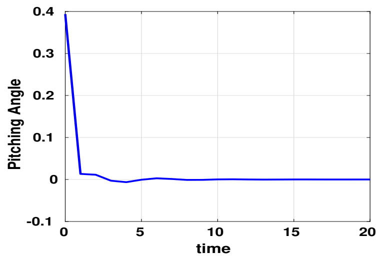
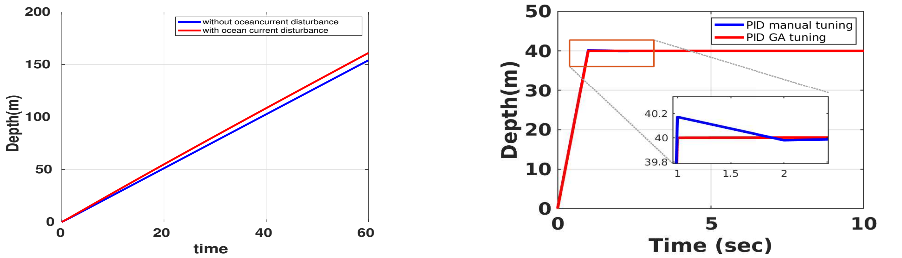


Fig. 14: Pitching responses of the AUV system using H_∞ controller (with wave disturbance)

(Assumption: Depth = 40m). All the simulation results are shown in Figure. 15 - Figure 18. From the comparison Table 8, found that the depth-pitch system providing excellent results while using H_∞ controller, but depth system with the presence of ocean current disturbance case it is giving slightly bad performance compared to PID controller with Genetic Algorithm tuning method.

Comparison of proposed controllers with existing systems : Several control strategies have been introduced in the velocity control area of the underwater vehicle. Table



(a) Open loop response,

(b) Controlled response using PID controller,

Fig. 15: Depth system response

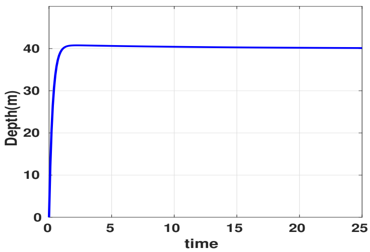
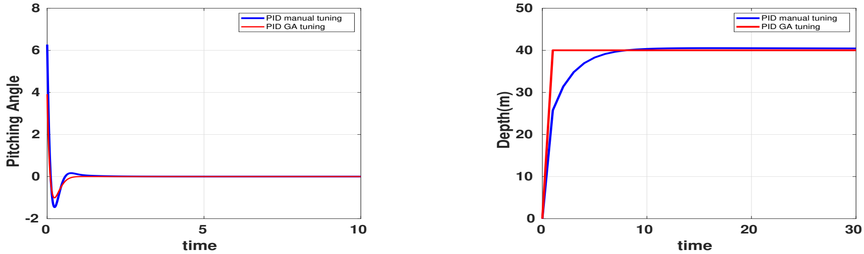


Fig. 16: Depth system response using H_∞ controller (without disturbance)



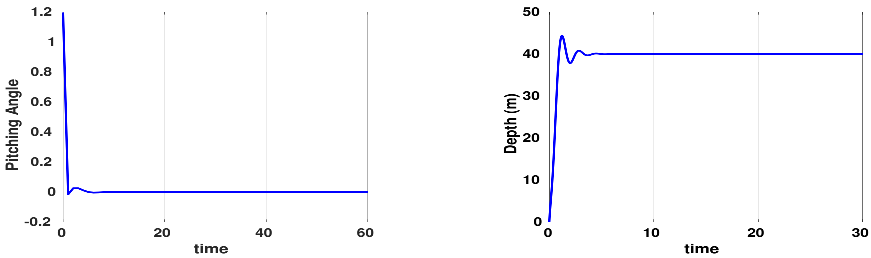
(a) Pitch system response,

(b) Depth system response,

Fig. 17: Controlled responses with ocean current disturbance using PID controller

9 illustrates the advantages and disadvantages of existing velocity control strategies of AUV.

In the case of depth system, the majority of the control application, dual loop design of the controller is used in which inner loop is pitch control, and outer loop is depth control. Table 10 exhibits the comparison of existing strategies of depth-pitch controller.



(a) Pitch system response,

(b) Depth system response,

Fig. 18: Controlled responses with ocean current disturbance using h_∞ controller

Table 8: Comparison of performance parameters of Depth-pitch tracking system

Pitch system without disturbance			
Performance parameters	**Controllers**		
	PID controller Manual tuning	**PID ontroller GA tuning**	**H-infinity controller**
Rise time (sec)	3.9489	2.4410	1.3579
Settling time (sec)	4.904	3.4891	1.7437
Overshoot (%)	15.0821	10.1607	9.7810
Pitch system subjected to wave disturbance			
Rise time (sec)	10.1400	8.2310	8.0071
Settling time (sec)	29.0315	22.0550	9.8907
Overshoot (%)	27.3571	20.4186	8.2579
Pitch system with ocean current disturbance			
Rise time (sec)	3.6191	3.0641	1.5468
Settling time (sec)	4.9028	2.4812	1.5180
Overshoot (%)	10.9518	4.5100	2.0185
Depth system without any disturbance			
Rise time (sec)	1.5100	1.4901	1.4328
Settling time (sec)	1.2834	1.0165	2.5170
Overshoot (%)	1.3813	1.3012	1.1296
Depth system with ocean current disturbance			
Rise time (sec)	7.4903	1.0108	1.0231
Settling time (sec)	8.1029	1.2081	5.8022
Overshoot (%)	2.2696	0.4810	2.4951

5 Conclusion

A velocity tracking control algorithm of AUV moving with a forward or surge velocity and a Depth-Pitch controller is proposed in this work. A comparison of performance measures of PID controller with manual tuning, Ziegler-Nichols method, Genetic Algorithm tuning, and H-infinity controller has been conducted.

Simulation results showed that the closed-loop system follows the input velocity of distinct magnitudes, regardless of how PID controllers are coordinated by the ordinary strategy, give a slightly substandard display and make appalling performance and higher resultant situation of outperforming. PID controller with genetic Algorithm tuning gave better results compared to Ziegler-Nichols tuning and manual tuning. H_∞ controller is giving the best results among all others. A dual loop depth controller design with inner pitch controller had been implemented and found that H

Table 9: Velocity controller comparison

Controller	Advantages	Disadvantages	Future development
PID controller	satisfactory performance, can be applied if the vehicle mass is not exactly known,	poor performance at the time of disturbance	issues concerning disturbance rejections will be studied, stability analysis in case of model uncertainties
MPC	acceptable set-point tracking performance,	takes longer time	require physical parameter modifications, sea trials
Fuzzy logic	good robustness in different underwater environments, acceptable accuracy	complexity of the system will increase, based on designer ability	sea trials

Table 10: Comparison of depth-pitch controller strategies

Controller	Control strategy	Vehicle model	Advantages	Disadvantages
SMC	Dual-loop depth-pitch control	STARFISH AUV	effective in controlling the depth, negligible steady state error.	chattering effect
		NSP AUV II	control precision, faster convergence, stronger robustness	disturbance effect does not considered
PID controller	Dual-loop depth-pitch control	NSP AUV II	settling time is somewhat satisfactory	less robust, low precision
PD controller	Dual-loop depth-pitch control	AUV	acceptable performance, non-linear dynamics considered	disturbance effect does not considered
PPD Controller	Dual-loop depth-pitch control	AUV (Myring hull profile)	performance of controllers meets the requirement	complexity high
Integral controller	Dual-loop depth-pitch control	AUV	Low overshoot and undershoot, low steady state error	transient response can be improved

infinity controller-based design is more efficient. Pitch controller is separately analyzed with different disturbance conditions. Pitch value made to be zero with and without disturbance conditions to keep the vehicle at a particular depth.

Acknowledgments. The author would like to thank Dr. P Ananthakrishnan, Department of Ocean Engineering, Indian Institute of Technology Madras for valuable assistance and support to do this research.

Declarations

- **Funding :** Not Applicable
- **Conflict of interest/Competing interests :** The author declare that there is no conflict of interest.
- **Ethics approval :** Not Applicable
- **Consent to participate :** Not Applicable
- **Consent for publication :** Not Applicable
- **Availability of data and materials :** Not Applicable
- **Code availability :** Not Applicable

- **Authors' contributions :** The author is contributed following concepts for this study; Conception, design, material preparation, analysis and editing

Appendix A BAUV hull specifications of the system

- Moment of Inertia: $I_x = 8.8\ Kg.m/s^2$, $I_y = 76.8\ Kg.m/s^2$, $I_z = 76.8\ Kg.m/s^2$, Mass $= 320Kg$
- Hydrodynamic co-coefficients of the AUV used in the system
$X_u = -11.91\ [Kg.s^{-1}]$, $X_{\dot{u}} = -81.81\ [Kg]$
$Z_{\dot{w}} = -235.62\ [Kg]$, $M_{\dot{w}} = 8.78\ [Kg.m]$
$Z_{\dot{q}} = -8.78\ [Kg.m]$, $Z_q = -250.21\ [Kg.m.s^{-1}]$

References

[1] Antonelli, G.: On the use of adaptive/integral actions for six-degrees-of-freedom control of autonomous underwater vehicles. IEEE Journal of Oceanic Engineering **32**(2), 300–312 (2007). https://doi.org/10.1109/JOE.2007.893685

[2] Fossen, T.I.: Handbook of Marine Craft Hydrodynamics and Motion Control. John Wiley & Sons, ??? (2011)

[3] Vahid, S., Javanmard, K.: Modeling and control of autonomous underwater vehicle (auv) in heading and depth attitude via ppd controller with state feedback. International Journal of Coastal and Offshore Engineering **4**, 11–18 (2016)

[4] Xiang, X., Chen, D., Yu, C., Ma, L.: Coordinated 3d path following for autonomous underwater vehicles via classic pid controller. IFAC Proceedings Volumes **46**(20), 327–332

[5] Kim, M., Joe, H., Kim, J., Yu, S.-c.: Integral sliding mode controller for precise manoeuvring of autonomous underwater vehicle in the presence of unknown environmental disturbances. Int. J. Control (88), 2055–2065 (2015)

[6] Yang, Y., Wang, Y., Manzie, C., Pu, Y.: Real-time distributed mpc for multiple underwater vehicles with limited communication data-rates. In: 2021 American Control Conference (ACC), pp. 3314–3319 (2021). IEEE

[7] Xiang, X., Yu, C., Lapierre, L., Zhang, J., Zhang, Q.: Survey on fuzzy-logic-based guidance and control of marine surface vehicles and underwater vehicles. Int. J. Fuzzy Systems **20**, 572–586 (2018)

[8] Sauot, O.: Computation of hydrodynamic coefficients and determination of dynamic stability characteristics of an underwater vehicle including free surface effects. PhD thesis, Florida Atlatic University (2003)

[9] Martin, A.K., Anathakrishanan, P., Krishnankutty, P.: Ship hull wake effect on the hydrodynamic performance of a heave–pitch combined oscillating fin. Ships and Offshore Structures, 1–11 (2020)

[10] Triantafyllou, M.S., Techet, A.H., Hover, F.S.: Review of experimental work in biomimetic foils. IEEE Journal of Oceanic Engineering **29**(3), 585–594 (2004)

[11] Lighthill, M.: Note on the swimming of slender fish. Journal of fluid Mechanics **9**(2), 305–317 (1960)

[12] Licht, S., Hover, F., Triantafyllou, M.S.: Design of a flapping foil underwater vehicle. In: Proceedings of the 2004 International Symposium on Underwater Technology (IEEE Cat. No. 04EX869), pp. 311–316 (2004). IEEE

[13] Theodorsen, T., Mutchler, W.: General theory of aerodynamic instability and the mechanism of flutter (1935)

[14] Harper, K.A., Berkemeier, M.D., Grace, S.: Modeling the dynamics of spring-driven oscillating-foil propulsion. IEEE Journal of Oceanic Engineering **23**(3), 285–296 (1998). https://doi.org/10.1109/48.701206

[15] Narasimhan, M.: Dorsal and Pectoral Fin Control of a Biorobotic Autonomous Underwater Vehicle. University of Nevada, Las Vegas, ??? (2005)

[16] Hammad, M.M., Elshenawy, A., Singaby, M.E.: Trajectory following and stabilization control of fully actuated auv using inverse kinematics and self-tuning fuzzy pid. PLoS ONE **12** (2017)

[17] Herman, P., Kowalczyk, W.: Velocity tracking control of auvs in horizontal motion. In: 2016 3rd Conference on Control and Fault-Tolerant Systems (SysTol), pp. 105–110 (2016). https://doi.org/10.1109/SYSTOL.2016.7739736

[18] J. G. Ziegler, N.B.N.: Optimum settings for automatic controllers. Journal of Dynamic Systems, Measurement, and Control **115**(2B), 220–222 (1993). https://doi.org/10.1115/1.2899060

[19] Jayachitra, A., Vinodha, R.: Genetic algorithm based pid controller tuning approach for continuous stirred tank reactor. Advances in Artificial Intelligence (16877470) (2014)

[20] Lin-Lin Wang, L.-X.P. Hong-Jian Wang: h_∞ control for path tracking of autonomous underwater vehicle motion. Advances in Mechanical Engineering **7** (2015)

[21] Randeep Kaur, J.O.: h_∞ controller design for pneumatic servosystem: A comparative study. International Journal of Automation and Control **8**(3) (2015)

[22] Bansal, A., Sharma, V.: Design and analysis of robust h-infinity controller.

Control theory and informatics **3**(2), 7–14 (2013)