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# Design of Fuzzy PD Depth Controller for an AUV

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## Abstract

This paper presents a design of fuzzy PD depth controller for the autonomous underwater vehicle entitled KAUV-1. The vehicle is shaped like a torpedo with light weight and small size and used for marine exploration and monitoring. The KAUV-1 has a unique ducted propeller located at aft end with yawing actuation acting as a rudder. For depth control, the KAUV-1 uses a mass shifter mechanism to change its center of gravity, consequently, can control pitch angle and depth of the vehicle. A design of classical PD depth controller for the KAUV-1 was presented and analyzed. However, it has inherent drawback of gains, which is their values are fixed. Meanwhile, in different operation modes, vehicle dynamics might have different effects on the behavior of the vehicle. In this reason, control gains need to be appropriately changed according to vehicle operating states for better performance. This paper presents a self-tuning gain for depth controller using the fuzzy logic method which is based on the classical PD controller. The self-tuning gains are outputs of fuzzy logic blocks. The performance of the self-tuning gain controller is simulated using Matlab/Simulink and is compared with that of the classical PD controller.

**Keywords:** Autonomous Underwater Vehicle, AUV, Torpedo-Shaped, Depth Control, Fuzzy Logic, Self-Tuning Gain, Mass Shifter Mechanism

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## 1. Introduction

Nowadays, autonomous underwater vehicle (AUV) is a research topic of great interest of many researchers in the world due to its extensively applied ability in marine economy and science, maritime security and navy. In addition to maneuvering precision, independent operating time of the vehicle is also a no less important factor. Therefore, torpedo-shaped AUVs which have low drag, so consume less energy, meaning that they can operate under water with a long time, have been interested in development. Common configuration of a torpedo-AUV includes a fixed propeller installed at the aft end, control planes (fins) for rudder and elevator located at the aft or bow as in Remus [1]. The weakness of this configuration is that it cannot work efficiently at low speeds. A more advanced configuration without any fins was applied for Bluefin [5]. In Bluefin, the propeller can be actuated in the horizontal and vertical directions basing on a double gimbal arrangement, acting as both rudder and elevator. The weakness of this configuration (and also of the previous configuration) is that performances of both depth controller and heading controller are strongly affected by nonzero roll, for example in case of a sharp turn, resulting in a performance not as good as expected [6]. Recently, Choi et al [11] proposed a new configuration for AUV which has been imple-

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mented on the vehicle named KAUV-1. It has a ducted propeller located at the aft end with yawing actuation acting as a rudder, a mass shifter mechanism used for changing vehicle center of gravity acting as an elevator. This configuration can somewhat fix the two aforementioned issues, meaning that the KAUV-1 can operate at low speeds and its performance of depth controller is affected very little by nonzero roll.

The vehicle usually has positive buoyancy to float to the surface in the event of a failure. So, at steady state the vehicle should have a slightly negative pitch to balance effect of positive buoyancy to keep its depth constant. Therefore, a classical PD controller using pitch error and derivative of pitch error for its inputs as in [11] will meet an asymmetric problem of input signals in modes of moving up and down. Such a controller with fixed gains will not result in the best performances as possible if control effective in both modes is considered.

This paper presents design of a self-tuning gain PD controller using fuzzy method to change values of the gains to achieve the best performances as possible for both modes of moving up and down.

## 2. Vehicle Specifications

The KAUV-1 has a length of 1.5 m and a maximum diameter of 0.18m. The vehicle has buoyancy of 23.8 kgf and weight of 23.4 kgf. Its center of buoyancy lies on the vehicle centerline and higher than its center of gravity for stabilization. To further enhance stability of the vehicle, three fixed planes are installed 120° apart on the aft. The features of the vehicle are shown in Fig.1.

The propulsion system is equipped with a propulsion motor inside to control the propeller which is protected by a ring-surface. The propulsion system can be steered to rotate around its vertical axis an angle up to 23° to each side by the yaw motor acting as a rudder as shown in Fig. 2.

The mass shifter mechanism used for depth control includes an LM guide actuator, a gear, a pitch motor, an encoder, and a movable mass fixed onto the LM block as in Fig. 3. The LM guide is attached to the underside of the horizontal supporting plate. When the movable mass goes forwards or backwards, the center of gravity of the whole vehicle also shifts forwards or backwards. This may make the vehicle tilted down or up. So, if the vehicle is propelled, it will go down or up respectively.

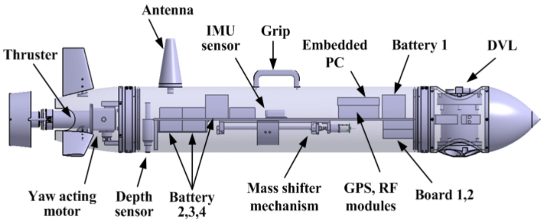


Fig. 1. Exterior view of the KAUV-1

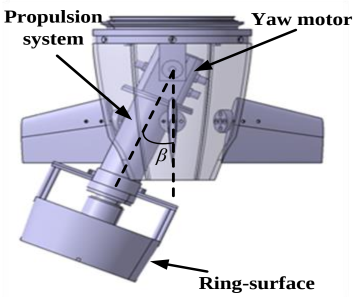


Fig. 2. The propulsion and rudder mechanism

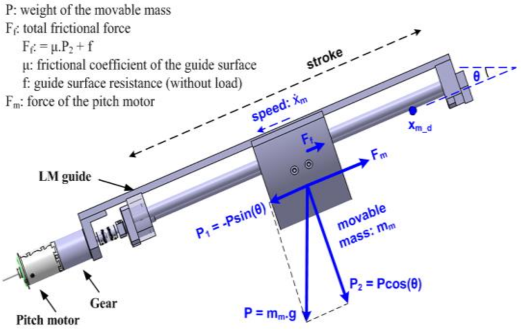


Fig. 3. The mass shifter mechanism

## 3. Classical PD Controller

Choi et al [11] proposed the strategy of depth control for the KAUV-1 as shown in Fig. 4. The depth error calculated from desired set-point and feedback values of the depth of the vehicle is multiplied by the proportional gain $\gamma$ to have the desired pitch angle $\theta_d$. Then, the pitch error $e_\theta$ will be calculated from the desired and feedback values of the pitch angle, and becomes the input of the PD depth controller. Its output is the desired value of x component coordinate of the movable mass $x_{m\_d}$. And then, the signal $x_{m\_d}$ is sent to the mass shifter actuator as a command. The mass shifter controller will drive the movable mass at position $x_m$ to reach

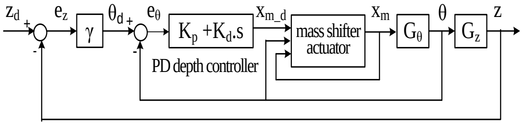


Fig. 4. Depth-plane control system block diagram

$x_{m\_d}$. With this control strategy, the vehicle will be driven to the desired depth effectively.

The pitch angle feedback signal is also sent to the input of the mass shifter actuator to estimate the projection of the weight of the movable mass on the axial axis. The controller must concern the influence of this force to give out a strong enough pitch motor force for driving the movable mass effectively.

Conventional positive sign and sense of related quantities are shown as in Fig. 5.

Simulation results in [11] show, at steady state, the movable mass stops at the position -0.05m instead of around 0m because of the influence of the body and plane lift and Munk moment whose value is proportional to surge and heave velocities and whose direction supports pitching down. To be fair to both modes of moving up and down, the stroke of LM guide in upcoming simulations is set as [-0.1 0]. However, in reality, the upper limit of this span should be greater than zero for the vehicle to be able to move down from the surface because it cannot pitch down when maximum position of the movable mass is just 0m and the body and plane lift and Munk moment at the surface is zero (due to heave velocity of zero).

Table 1. Initial states used in simulations

| Surge velocity, u | Heave velocity, w | Pitch angle, θ | $x_m$ |
|---|---|---|---|
| 1.5 m/s | -0.08 m | $-3.07^o$ | -0.05m |

In this paper, simulations are performed with initial states which are similar to steady states as listed in Table 1.

As mentioned before, due to the asymmetry of input signals, a classical PD controller with fixed gains will not bring the best results as possible for both modes of moving up and down. For example, the controller I with gains as listed in Table 2 designed specifically to have a critically damped response in mode of moving down for a depth change of 2 m (settling time $T_s$ = 8.5s) will result in a underdamped response in mode of moving up ($T_s$ = 15.2s, overshoot = -0.24m) as shown in Fig. 6. In contrast, the controller II with gains as listed in Table 3 designed specifically to have a critically damped response in mode of moving up for a depth change of 2 m ($T_s$ = 8.2s) will result in a overdamped response in mode of moving down ($T_s$ = 19s) as shown in Fig. 7.

In the next section, the design of a self-tuning gain controller will be presented. This controller can result in better responses for the both modes. Furthermore, it is proved to work better than the classical PD controller in case of commands out of standard design.

Table 2. Controller gains (Controller I)

| **γ** | **$K_p$** | **$K_d$** |
|---|---|---|
| -0.387 | -0.906 | -2.5 |

Table 3. Controller gains (Controller II)

| **γ** | **$K_p$** | **$K_d$** |
|---|---|---|
| -0.346 | -0.906 | -2.35 |

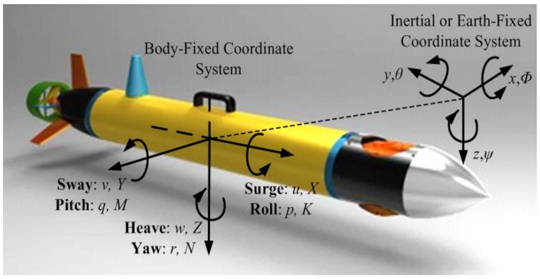


Fig. 5. Body-fixed and inertial coordinate systems

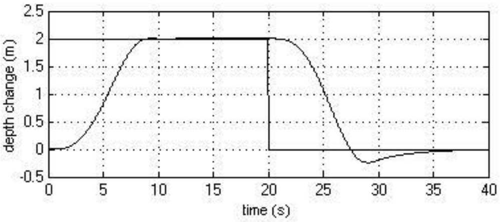


Fig. 6. Depth change with the controller I

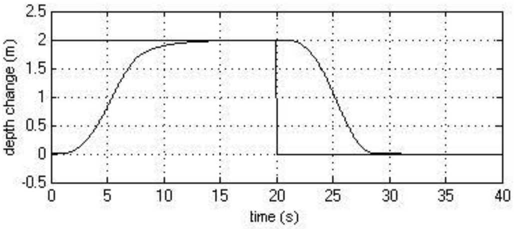


Fig. 7. Depth change with the controller II

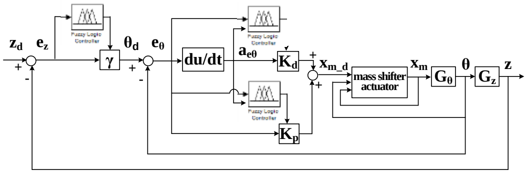
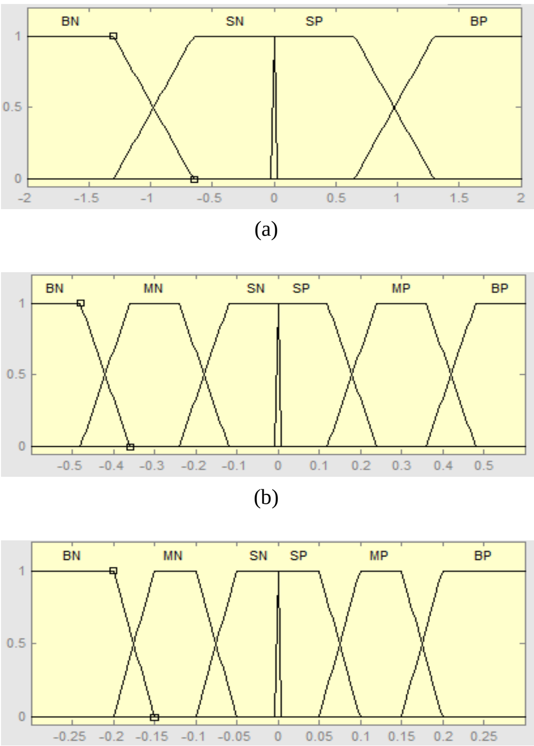


Fig. 8. Depth-plane control system block diagram with self-tuning gains

## 4. Self-Tuning Gain Controller

The self-tuning gain controller is designed based on the classical PD controller [11] as shown in Fig. 8.

The gains $\gamma$, $K_p$, $K_d$ are the outputs of the corresponding fuzzy blocks. The input of the fuzzy block $\gamma$ is only the depth error $e_z$. The inputs of the fuzzy blocks $K_p$, $K_d$ are the pitch error $e_\theta$ and derivative of pitch error $a_{e\theta}$. The membership functions of the depth error, pitch error, derivative of pitch error are given in Fig. 9. The membership functions of the gains $\gamma$, $K_p$, $K_d$ are given in Fig. 10. The fuzzy rules for the gain $\gamma$ are given in Table 4, and for the gains $K_p$, $K_d$ are given in Table 5.

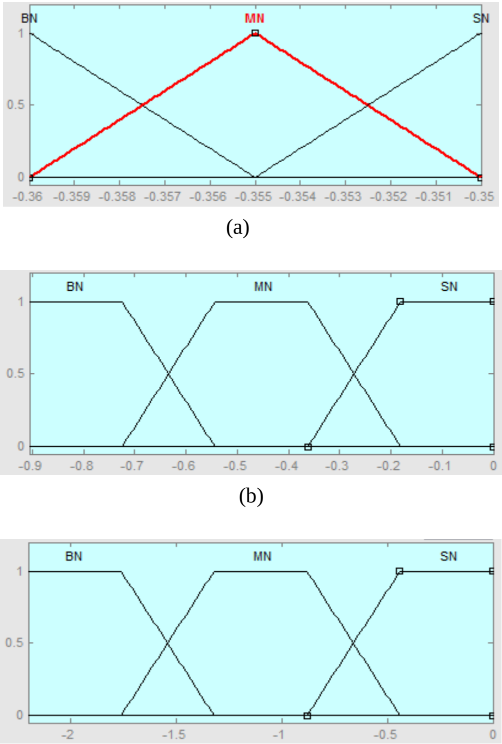


(a)

(b)

(c)

Fig. 9. The membership functions of the depth error (a), pitch error (b), derivative of pitch error (c)



(a)

(b)

(c)

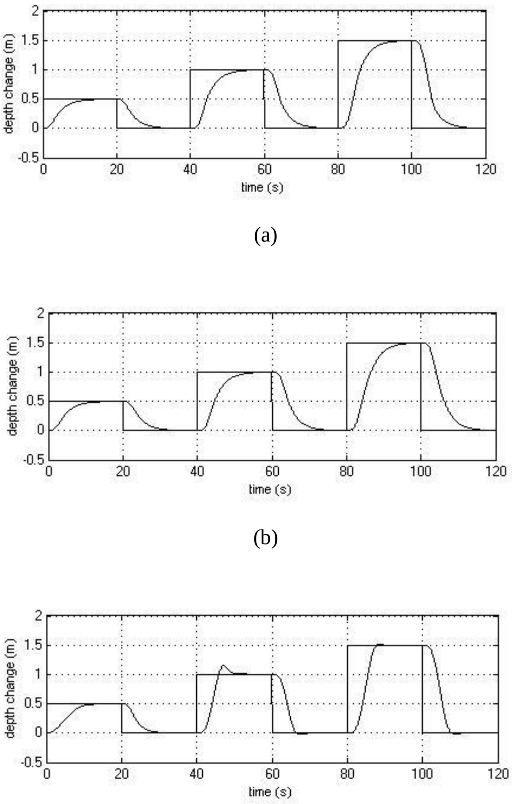
Fig. 10. The membership functions of the gains $\gamma$ (a), $K_p$ (b), $K_d$ (c)

Table 4. The fuzzy rules for the gain γ

| γ | Depth Error | | | |
|---|---|---|---|---|
| | BN | SN | SP | BP |
| | MN | SN | SN | BN |

Simulation result with the self-tuning gain controller given in Fig. 11 shows good responses for both mode of moving down ($T_s$ = 8.5s) and up ($T_s$ = 8.3s).

In case of a command out of standard design, for example, a smaller depth change of 0.5m or 1m or 1.5m instead of 2m is given, the self-tuning gain controller shows faster responses than the classical PD controllers as shown in Fig. 12 except small overshoots of 0.15m and 0.016m in case of the depth changes of 1m and 1.5m respectively.



(a)

(b)

(c)

Fig. 12. Depth change in case of input uncertainties with the controller I (a), controller II (b), self-tuning gain controller (c)

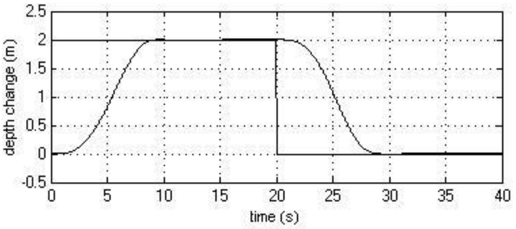
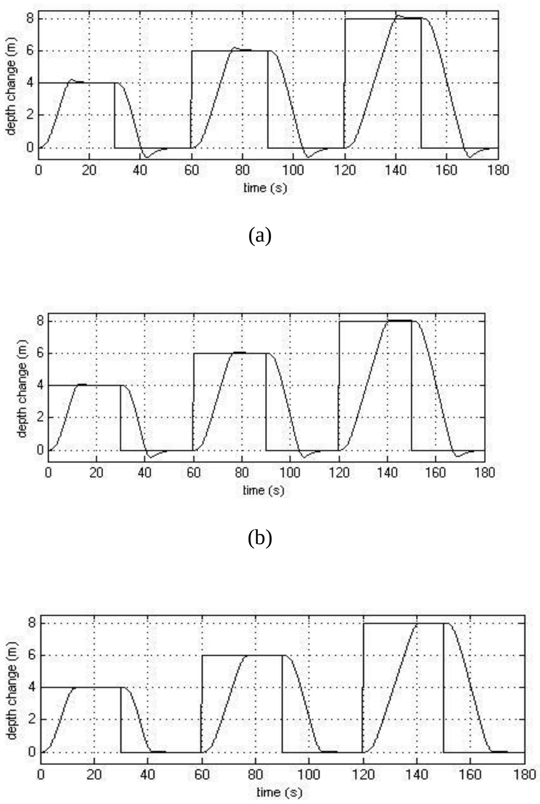


Fig. 11. Depth change with the self-tuning gain controller

Especially, in case of greater depth changes of 4m or 6m or 8m, the self-tuning gain controller is more robust performance than the classical PD controllers as shown in Fig. 13. Its response does not have overshoot. Meanwhile, the responses of the classical PD controllers have great overshoots especially in mode of moving up.



(a)

(b)

(c)

Fig. 12. Depth change in case of input uncertainties with the controller I (a), controller II (b), self-tuning gain controller (c)

Table 5. The fuzzy rules for the gain $K_p$, $K_d$

| $K_p$<br>$K_d$ | | Pitch Error | | | | | |
|---|---|---|---|---|---|---|---|
| | | BN | MN | SN | SP | MP | BP |
| Derivative of Pitch Error | BP | BN<br>MN | BN<br>SN | BN<br>MN | SN<br>SN | BN<br>BN | BN<br>BN |
| | MP | BN<br>MN | BN<br>SN | BN<br>SN | SN<br>SN | BN<br>BN | BN<br>BN |
| | SP | BN<br>MN | BN<br>BN | SN<br>BN | BN<br>MN | BN<br>BN | BN<br>BN |
| | SN | BN<br>BN | BN<br>BN | SN<br>SN | BN<br>BN | BN<br>BN | BN<br>MN |
| | MN | BN<br>BN | BN<br>BN | SN<br>SN | BN<br>BN | BN<br>MN | BN<br>MN |
| | BN | BN<br>BN | BN<br>BN | SN<br>SN | BN<br>MN | BN<br>MN | BN<br>MN |

## 5. Conclusions

The paper presents a design of self-tuning gain depth controller using fuzzy logic method for the KAUV-1. Simulation results show it can deal with the asymmetry of input signals, an impossible mission to the classical PD controllers, so results in better performances in both modes of moving up and down of the vehicle. Moreover, it is also proved to work better in case of commands out of standard design. This means the number of controllers needed to be designed for operation of the vehicle can be reduced. The future work will be testing the performance of the self-tuning gain controller in face of uncertainties.

## Acknowledgement

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