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Kalman Filter and PID Application on Underwater Vehicles

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ROV (Remoted Operating Vehicle)

R E S E A R C H   A R T I C L E

A B S T R A C T

Unmanned underwater vehicles (ROV/AUV) are autonomous or remotely controlled robotic systems that can move underwater at any desired angle. Unmanned underwater vehicles; It is used in areas such as underwater image taking, ship maintenance and repair, coast guard, examination of shipwrecks, underwater cleaning. In this study, the software design of the balance control of underwater vehicles was carried out using the PID algorithm. For the PID algorithm trial, a two-motor test setup with an IMU sensor was prepared. After the data from the sensor were recorded in MATLAB using the Kalman filter, the transfer function of the system was obtained using the System Identification Toolbox. With the obtained transfer function, the stable operation of the system is provided in real time. As a result of the research on software and hardware integration, microcontroller ARM-based STM32 was used.

1. Introduction

Today, unmanned underwater vehicles are used in different fields. It is used in areas such as underwater search and rescue operations, ship underwater maintenance and repair operations, taking images from dangerous environments that divers cannot enter, military use, examination of shipwrecks, and underwater cleaning [1].

When the literature studies in this field were examined, Abidin et al. developed and successfully applied the Proportional Integral Derivative (PID) algorithm with the depth sensor data found in the underwater vehicles [2]. Li et al., by communicating the Inertial Measurement Unit (IMU) sensor with the STM32 microcontroller, read the incoming data meaningfully. Observing that the incoming data is noise, they could stabilize the data by performing a Kalman Filter (KF) and angle fusion study on the data. To ensure the balance of the two-wheeled vehicle, they gave the necessary PWM output to the motors with the PID algorithm according to the data coming from the IMU [3]. Prasetio applied an Ensemble Kalman Filter (EnKF), a sub-branch of KF, to receive IMU data with the Arduino Nano microcontroller and remove the noises. A PID algorithm was created with filtered sensor data to ensure the stability of the two-wheeled vehicle [4]. Ekmen and his friend obtained a mathematical model of the system according to the x and y coordinate data of the images from the camera on the drone and achieved an autonomous landing [5].

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In this study, a two-engine test setup was prepared. After the data from the sensor were recorded in MATLAB using KF, the transfer function of the system was obtained using the System Identification Toolbox. The PID controller is designed with the obtained transfer function. For the vehicle to maintain its balance despite disruptive effects such as underwater currents, the filtered sensor data is used in the PID algorithm to ensure the stable operation of the system in real time.

2. Materials And Method

2.1. Underwater vehicles

Underwater vehicles can have 2 or 4 motors to move vertically and maintain their balance. As shown in Figure 1, the vehicle used in the project has 2 engines to move vertically and balance in the water, apart from 4 engines that provide horizontal mobility. Before being tested in water, the software tests of the system were carried out with 2 motorized test setups given in Figure 2.

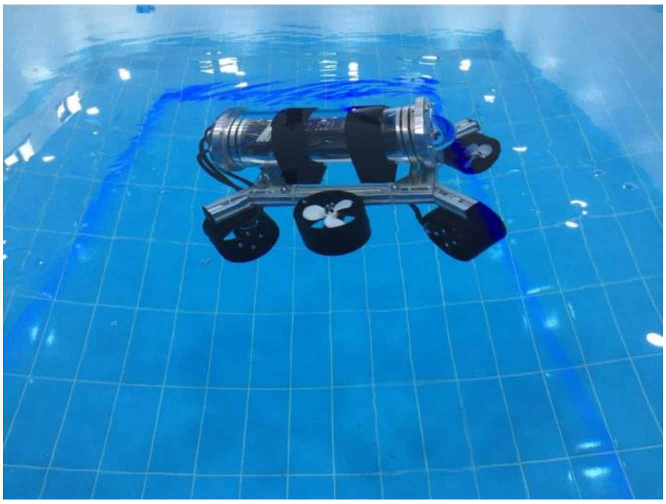

Figure 1. RACLAB – NOVA underwater vehicle

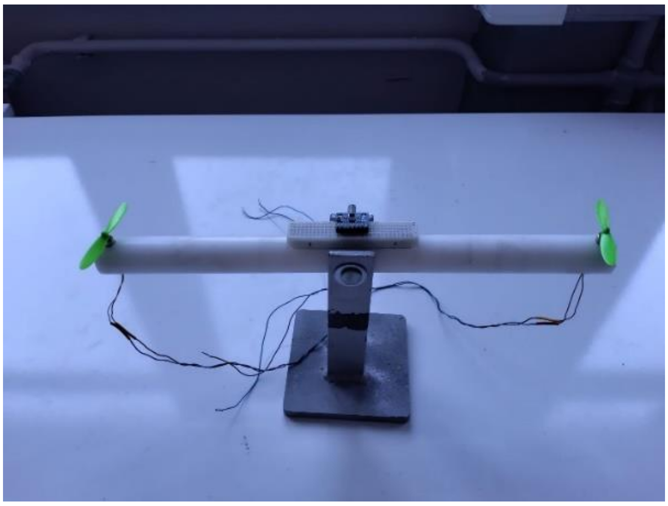

Figure 2. PID tester

2.2. Kalman filter

In a dynamical system represented by the KF state space model, it is an algorithm that provides estimates of unknown variables given the measurements observed over time.

The general formula of KF is expressed in “(1)” and the matrix is formed “(2)”. The covariance matrix shows that our variables have a random Gaussian distribution, and its mathematical expression is given in “(3)”.

$$\overrightarrow{x_k} = (\theta, v) \tag{1}$$

$$\overrightarrow{x_k} = \begin{bmatrix} \theta \\ v \end{bmatrix} \quad (2)$$

$$P_k = \begin{bmatrix} E_{\theta\theta} & \sum \theta v \\ \sum v\theta & \sum vv \end{bmatrix} \quad (3)$$

The algorithm takes all possible points in the prediction and switches to the newly predicted state. In this way, it covers all possibilities. The mathematical expression of the situation is given in "(4)" and "(5)". The matrix form is expressed in "(6)" and "(7)". The distribution matrix is expressed in "(8)". If the distribution matrix is multiplied with another matrix A, the result obtained is obtained as in "(9)". If "Equations (7) and (9)" are combined, the mathematical formula "(10)" is obtained. To include external influences in the system, the acceleration 'a' must be defined. The mathematical model formed when the system acceleration 'a' is added is expressed as in "(11)" and "(12)". The general formula for the representation of the system with a matrix "(13)" is expressed in "(14)" [6].

$$\theta_k = \theta_{k-1} + r\Delta t v_{k-1} \quad (4)$$

$$v_k = v_{k-1} \quad (5)$$

$$\hat{x}_k = \begin{bmatrix} 1 & \Delta t \\ 0 & 1 \end{bmatrix} \hat{x}_{k-1} \quad (6)$$

$$\hat{x}_k = F_k \hat{x}_{k-1} \quad (7)$$

$$\text{Cov (x)} = \sum \quad (8)$$

$$\text{Cov (Ax)} = \text{A} \sum A^T \quad (9)$$

$$P_k = F_k P_{k-1} F_k^T \quad (10)$$

$$\theta_k = \theta_{k-1} r\Delta T v_{k-1} + \partial \Delta t^2 \quad (11)$$

$$v_k = v_{k-1} + \partial \Delta t^2 \quad (12)$$

$$\hat{x}_k = F_k \hat{x}_{k-1} + \begin{bmatrix} \Delta t^2 \\ \Delta t \end{bmatrix} \partial \quad (13)$$

$$\hat{x}_k = F_k \hat{x}_{k-1} + B_{k\,\widehat{Uk}} \quad (14)$$

Here, 'BK' denotes control matrix and 'UK' denotes control vector. KF will be implemented on the IMU sensor, which will be used in routing the PID algorithm.

2.3. PID controller

The PID controller control loop method is a widely used feedback controller method in industrial control systems. A PID controller continuously calculates an error value, ie the difference between the intended system state and the current system state. The controller tries to minimize the error by adjusting the process control input.

The PID algorithm controls three separate constant parameters to reduce the error value. Proportional (P) is based on current error, Integral (I) is the sum of past errors and Derivate (D) is an estimate of future errors [7]. The controlled process through the weighted sum of these three actions is used to adjust to the desired level.

For the system output to follow the desired reference value in PID control, the Kp, Ki, Kd coefficients must be adjusted appropriately. The output is obtained by multiplying e(t) with the proportional term of the error signal Kp, the integral of the error signal with the integral term Ki, and the derivative of the error signal with the derivative term Kd. The general formula of the PID algorithm is shown in "(12)" and the calculation of the error occurred in "(13)". The effects of each PID coefficient on the system are given in Table 1.

$$u(t) = K_p * e(t) + K_i \int e(t)dt + K_d \frac{d}{dt} e(t) \quad (12)$$

$$e(t) = r(t) - y(t) \quad (13)$$

Table 1. Effects of PID coefficients on the system

Parameters				
Factor	**Rise Time**	**Overshoot**	**Seating Time**	**Persistent State Error**
K_p	Reduces	Increase	Low impact	Reduces
K_i	Low impact	Reduces	Reduces	Annihilates
K_d	Reduces	İncrease	İncrease	Low impact

3. Result

There is an IMU sensor inside the underwater vehicle to ensure its balance in the water. The raw data were obtained by serial communication between the microcontroller and the sensor. The data obtained without the application of CF are shown in Figure 3. The angle that the sensor makes with respect to the X-axis is observed. It has been observed that the raw sensor data varies between 9° and 23° due to noise. When these change values are examined, it has been determined that the system prevents it from reaching the equilibrium position. It was decided to apply KF to eliminate the noise. We observed that the data obtained after SF was applied to the sensor data were stable and their values varied between 14.68° and 14.77°. The data obtained after applying CF are shown in Figure 4.

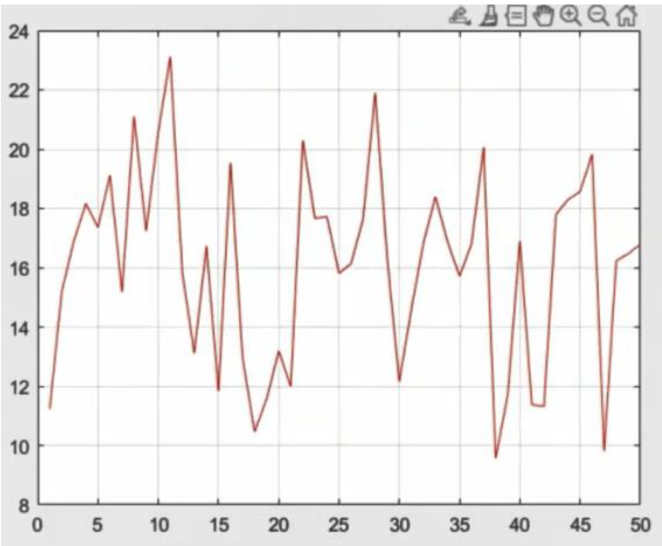

Figure 3. Kalman unapplied IMU data

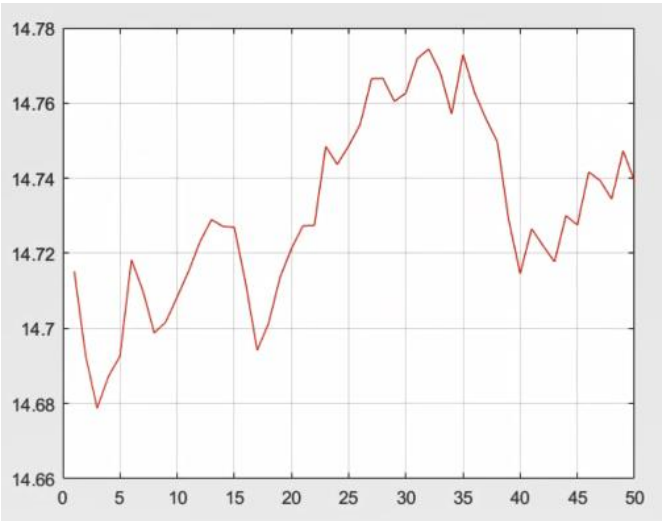

Figure 4. Kalman applied IMU data

The mathematical model of the system was created by sending the PWM values (Output) corresponding to the filtered sensor data (Input) to the MATLAB program via serial communication. As a result of 7 iterations, the most appropriate transfer function was obtained for the values entered the system. The created mathematical model for the test setup is given in Figure 5.

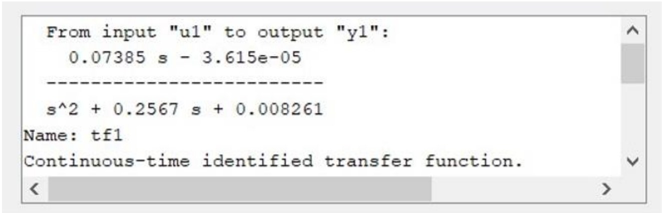
```
  From input "u1" to output "y1":
    0.07385 s - 3.615e-05
  -------------------------
  s^2 + 0.2567 s + 0.008261
Name: tf1
Continuous-time identified transfer function.
```

Figure 5. Mathematical model of the system

Output values corresponding to the input values of the system with a sampling time of 50ms were sent to the MATLAB program via serial communication. The first 10 examples are given in Table 2.

Table 2. PID input and output value

Time (ms)	PWM Value (Input)	Gyro Value (Output)
0.05	114.323	3.321
0.10	114.072	2.708
0.15	110.457	2.289
0.20	102.737	2.233
0.25	102.720	2.159
0.30	107.318	1.862
0.35	109.632	1.470
0.40	106.285	1.251
0.45	110.377	0.856
0.50	108.658	0.569

A mathematical model and PID algorithm were installed in the MATLAB Simulink program, which is used for modelling, simulation, analysis and testing of embedded systems, and a controller was designed. The established algorithm is shown in Figure 6.

The unit step response of the system is shown in Figure 7 by selecting the optimum Kp, Ki and Kd values in the simulation environment. It has been observed that the system response quickly follows the unit step response. KF was applied by reading the sensor data with the determined PID coefficients, and then the PID algorithm was embedded in the ARM-based STM32F401 microcontroller.

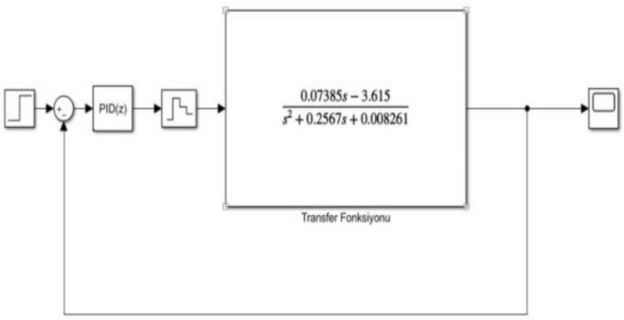

Figure 6. PID control block diagram

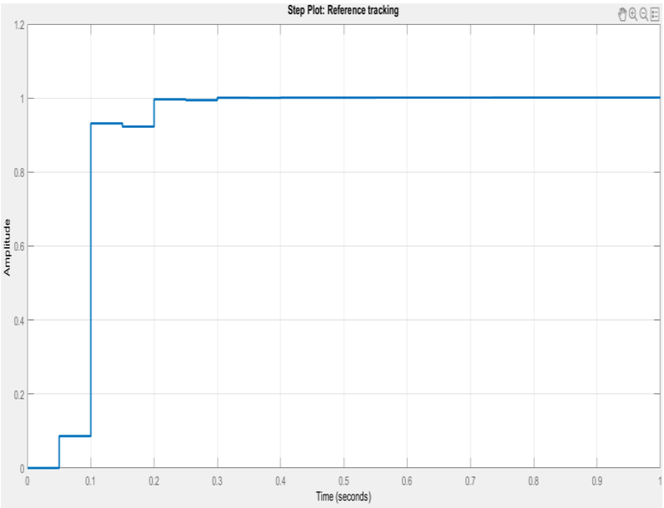

Figure 7. Simulation unit step response of the system

4. Discussion

With the increasing interest in underwater vehicles, there is a need to develop a controller to be used in these vehicles. When the literature is examined, it has been observed that simple control techniques such as PID have been applied successfully in such systems.

The number of ROVs/AUVs with domestic software on the market is considered insufficient. Based on this inadequacy, a PID controller was designed to support the locality. For the realization of the project, the most suitable microcontroller was researched, and it was decided to use the ARM-based STM32F401. The data from the sensor were filtered with KF. After the input and output data were recorded in MATLAB using serial communication, the transfer function of the system was obtained using the System Identification Toolbox. The PID controller is designed with the obtained transfer function. The filtered sensor data has been integrated into the PID algorithm to ensure the stable operation of the system in real time to ensure the vehicle's stability against disruptive effects such as underwater currents.

The results obtained from this study can be easily used in the field of defence industry. The results obtained at the end of this study will lead to the development of new projects related to ROV/AUV. The data obtained from this study will be a source for future studies on this subject.

5. Conclusion

The results obtained from this study can be easily used in the field of defence industry. The results obtained at the end of this study will lead to the development of new projects related to ROV/AUV. The data obtained from this study will be a source for future studies on this subject.

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