

# Fuzzy Logic PID Based Control Design for a Small Underwater Robot with Minimum Energy Consumption

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**Abstract**—In this paper, various mechanical and electrical constituting parts of autonomous submarines are discussed. In particular, one of the major units, the control unit, was investigated and a microcontroller designed. Based on Fuzzy Logic and PID control approaches, it is intended to be used in small autonomous underwater robots. This special architecture enables the robot to respond fast enough and provides higher levels of deliberation and perception as well as reliable performance in the robot's activities. Also, an intelligent system of temperature and energy control was designed to let the robot move as much as possible with minimum energy consumption.

**Index Terms**—Autonomous Underwater Robot (AUV), Fuzzy Logic Controller (FLC), PWM, Proportional Integral Derivative (PID)

## I. INTRODUCTION

Nowadays, small autonomous underwater robots are strongly preferred for remote exploration of unknown and unstructured environments. Such robots allow the exploration and monitoring of underwater environments where a long term underwater presence is required to cover a large area. Furthermore, reducing the robot size, embedding electrical board inside and reducing cost are some of the challenges designers of autonomous underwater robots are currently facing.

As a key device for reliable operation-decision process of autonomous underwater robots, a relatively fast and cost-effective controller based on Fuzzy logic and Proportional-Integral-Derivative (PID) method is proposed. It efficiently models nonlinear system behaviors largely present in robot operation and for which mathematical models are difficult to obtain. To evaluate its response, the fault finding test approach was applied and the response of each task of the robot depicted under different operating conditions. Then, the robot control unit including interrelated sensors was demonstrated.

## II. MECHANICAL AND ELECTRONIC COMPONENTS TYPE

Because an efficient design of the control unit requires a deep understanding on how the different mechanical and electronic components interconnecting with that unit will

operate and/or exchange data between the surrounding environment and the robot, a prior investigation was achieved on the performance of the different mechanical/electronic parts (including sensors) that directly embed the control unit.

### A. Microcontroller-Schematic

The type of microcontroller used in this work is a P89V51RD2 with 64 kB flash. Its priority allows using it in both state, X2 mode (6 clocks on machine cycles to reach twice the throughput at the same clock frequency) and the conventional 80C51 clock rate (12 clocks on machine cycle).

The flash state supports both parallel programming (increasing the programming speed as well as reducing its expense, thus saving additional time) and serial programming (which allows the device to be programmed) [1], [2].

### B. Microcontroller-Schematic

To assure adequate moving under water in both vertical and horizontal directions, the robot has been equipped with four motors. These motors should have sufficient power to move but also the smallest possible volume according to the shape and size of the robot as well as consuming minimum power and creating minimum noise and oscillations.

According to these constraints, RS-380 motors have been used with suitable blades as well as high torque and proper speed while the robot's electrical power is provided via a 12V battery installed below the robot.

## III. FUZZY DESIGN PROCESS

A static or dynamic system, which makes use of fuzzy sets or fuzzy logic and of the corresponding mathematical framework, is called a fuzzy system. Most common are fuzzy systems defined by means of if-then rules with fuzzy predicates. Fuzzy systems can serve different purposes, such as modeling, data analysis, prediction or control. Historically, automatic control was among the first technical application domains of fuzzy systems [3], [4]. The basic idea of a Fuzzy Logic Controller (FLC) is to formulate the control strategy of a human operator, which can be represented as a collection of if-then rules, in a way tractable for computers and for mathematical analysis [5]-[8].

The FLC is indeed a system that applies linguistic rules to a given input vector to compute an output vector. The fuzzy design process for embedded controller can be executed in three main steps including fuzzification of the inputs, inferencing the rule based knowledge and defuzzification of the output [9].

#### IV. PID CONTROL

A Proportional-Integral-Derivative (PID) controller is a control loop feedback mechanism widely used in industrial control systems. A PID controller calculates an "error" value as the difference between a measured process variable and a desired set point [10].

The PID controller algorithm involves three separate constant parameters and is accordingly called three-term control; P stands for proportional, I for integral, and D for derivative [11]. It is described by:

$$u(t) = k \left( e(t) + \frac{1}{T_i} \int_0^t e(\tau) d(\tau) + T_d \frac{de(t)}{dt} \right) \quad (1)$$

where  $u$  the control signal and  $e$  the control error. The reference variable is often called the set point.

The control signal is thus a sum of three terms: the P-term (proportional to the error), the I-term (proportional to the integral of the error), and the D-term (proportional to the derivative of the error). The controller parameters are proportional to the gain  $K$ , the integral time  $T_i$ , and the derivative time  $T_d$  [11].

#### V. PROGRAMMING MICROCONTROLLER USING TILT SENSOR AND FUZZY PI CONTROL

One of the issues of the fuzzy control in dynamic systems is that they cannot be forecasted. The balanced error is one of the main factors that needs time to reach the desirable situation. One of the ways is to use the fuzzy PI controller to reduce the risk in the situation of robots balance. The fuzzy program was then written using the following instructions [9]:

Fuzzy P rules:

IF Tilt-error is Positive Small THEN P-PWM is Positive Big, IF Tilt-error is Positive Small AND Tilt-Error is Zero THEN P-PWM is Positive Medium, IF Tilt-Error is Zero THEN P-PWM is Zero, IF Tilt-Error is Positive Small AND Tilt-Error is Zero THEN P-PWM is Positive Medium, IF Tilt-error is Positive Medium THEN P-PWM is Positive Big, IF Tilt-Error is Positive High THEN P-PWM is Positive High.

Fuzzy I rules:

IF Integral is Positive Small THEN I-PWM is Positive Big, IF Integral is Positive Small AND Tilt-Error is Zero THEN I-PWM is Positive Medium, IF Integral is Zero THEN I-PWM is Zero, IF Integral is Positive Small AND Tilt-Error is Zero THEN I-PWM is Positive Medium, IF Integral is Positive Big THEN I-PWM is Positive Big.

When the values for P and I membership functions are: P: PS = -60, Zero = 0, PM = 100, PB = 160 and I: PS = 40, PB = 80.

The corresponding Fuzzy PI surface is plotted in Fig. 1.

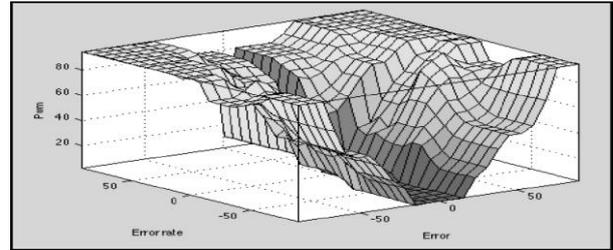


Figure 1. Fuzzy PI surface.

#### VI. PROGRAMMING MICROCONTROLLER USING TEMPERATURE SENSOR AND FUZZY PI CONTROL

One of the drawbacks in small AUVs is the heat generated by the motors and batteries. Thus, we should maintain a constant temperature inside the robot. An intelligent fuzzy-based temperature control system was then designed. With  $E$  representing the Error and  $\Delta E$  the Error rate.

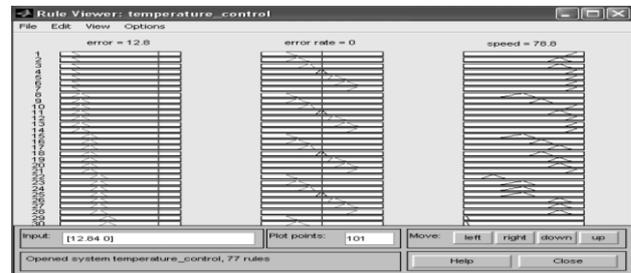


Figure 2. Temperature controller simulation for a 13 °C change in temperature.

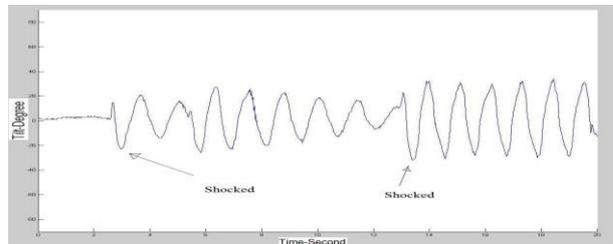


Figure 3. First response of the robot without fuzzy program. (0s-3s: stable, 3s-14s: create a shock, 14s-20s: response did not improve).

When the robot is subject to a sudden increase of heat, the system is able to change from a critical condition to a stable condition. This happens because of the high value of the PWM value in the output membership function. As shown in Fig. 2, the robot has been able to balance temperature rapidly, at about 78% of the fans speed, after a sudden increase of temperature by 13 °C.

#### VII. DATA COLLECTION

##### A. Experiments in Underwater Using Sensors and Fuzzy PI Control

Then, experiments were performed underwater using the Fuzzy P control. As seen in Fig. 3, when the robot is exposed to a small deviation shock, around 20 degrees, it cannot stabilize its position and even the instability increased due to the high value of PWM in the output

membership function. This part of the fuzzy program results in the robot's response. Thus, by changing the membership function from 150 to 200, new results were observed as shown in Fig. 4.

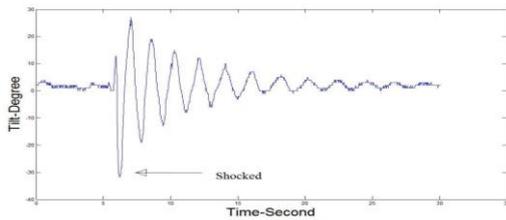


Figure 4. Tuned fuzzy output. (0s-5s: stable, 5s-10s: create a shock, 10s-30s: shock is absorbed).

This figure shows that even after a large deviation shock, around 30 degrees, the robot quickly reaches equilibrium but not yet a stabilized situation because of slower motors' response. In fact, reduction in the PWM value resulted in lower motor power (Fig. 5). Hence, it should not happen since the robots are expected to perform properly.

When the shock exceeds about 60 degrees more than the first shock, the motors efficiency maximize their performance and accordingly, the PWM value could be reduced and thus, better results may be obtained by changing the membership functions. Also, after a period of time, the internal temperature increases inside the robot. The designed temperature control system adapted the membership functions for Low membership to start from -5 and high membership function to start from +5. The output PWM values for medium and high are 250 and 450, respectively. As seen in Fig. 6, the robot is therefore more stabilized that in the last experiment.

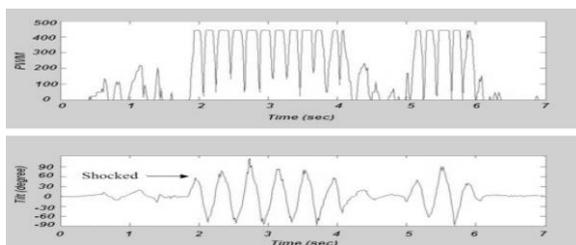


Figure 5. Response of fuzzy PWM and tilt without temperature control system. (0s-2s: stable, 2s-4s: create a shock, 4s-7s: response did not improve).

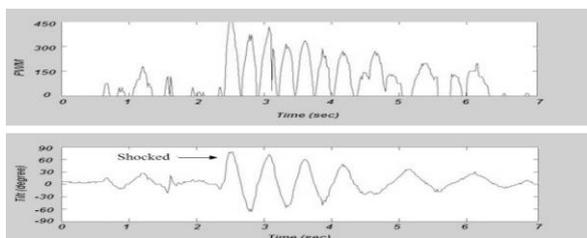


Figure 6. Response of fuzzy PWM and tilt with temperature control system (0s-2.5s: stable, 2.5s-4s: create a shock, 4s-7s: shock is absorbed).

### B. Experiments in Underwater Using Tilt Sensor and Fuzzy PI Control

As mentioned, one way of reducing steady-state error is using Fuzzy PI; thus, underwater experiment was

performed using a Fuzzy PI controller. At first, the values for P and I membership functions were set as:

P: PS = -60, PM = 100, PB = 160 and I: PS = 40, PB = 80.

The output of the PWM is based on the PI's mathematical equation. First, the fuzzy PI was not tuned and the response of the system was with predefined variables. As seen in Fig. 7, the robot was unable to be balanced and was going to oscillate.

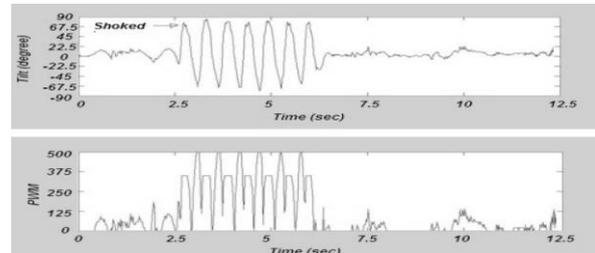


Figure 7. First response of the fuzzy PI. (0s-2.5s: stable, 2.5s-3s: create a shock, 3s-5.5s: shock begins to rise and 6s-12.5s: unstable response).

Then, we tuned the fuzzy variables. The new values for P and I membership functions were set as:

P: PS = -40, PM = 500, PB = 650, and I: PS = 70, PB = 60

The response of the system with these new values is depicted in Fig. 8. By comparing the obtained results, it can be stated that the balanced error fades but it is still very sensitive and might get out of the balanced condition with slight changes.

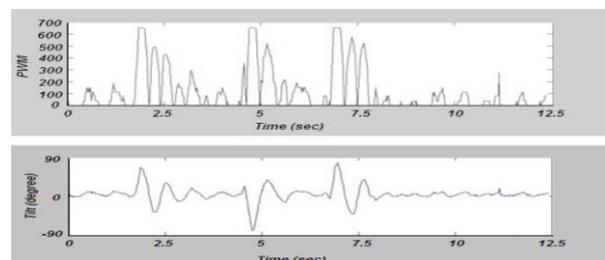


Figure 8. Last tuning of fuzzy PI (0s-2s: stable, 2s-2.5s: create a small shock, 2.5s-4.5s: shock absorbed, 4.5s-5s: create a small shock, 5s-6s: shock absorbed).

As for the forward movement of the robot using spinning horizontal motors, we performed a first experience without neither the feedback nor the controller system to manage the robot balance and stabilization (Fig. 9). As expected, the robot's gradient increased when it is moving forward, and then reaches zero when it stops.

After adding feedback and fuzzy logic to the gradient value and by regulating the final settings of the fuzzy PI, the robot's movements become more stabilized as shown in Fig 10.

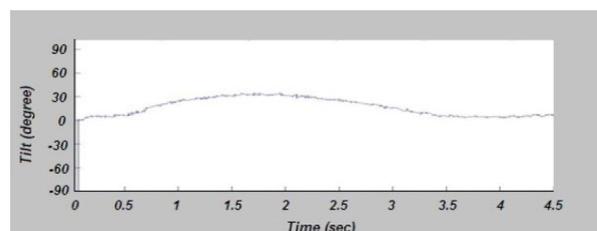


Figure 9. Tilt's changes, without control feedback, when the robot is moving forward.

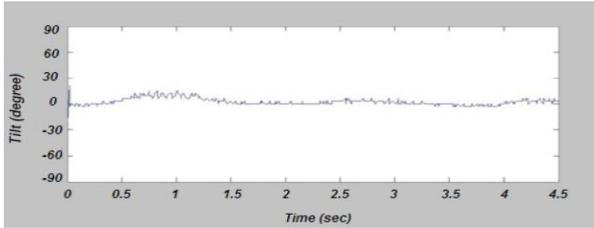


Figure 10. Tilt's changes, with fuzzy control, when the robot is moving forward.

### C. Experiments in Underwater Using Compass Sensor and PI Control

We then used the two horizontal motors installed on the robot. However, these two motors were not able to move in the same direction without the help of the PI control feedback (Fig. 11). However, by introduced the PI control, the robot's response, sent as two different values from the PI controller motors, is significantly improved as shown in Fig. 12 and Fig. 13.

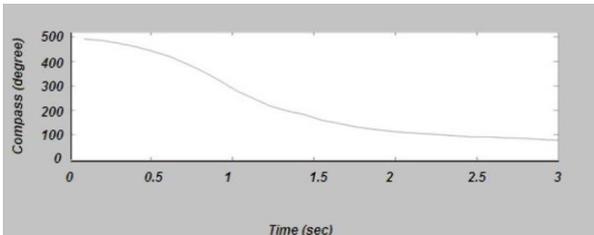


Figure 11. Change of compass's degree, when the robot is moving forward without Control feedback.

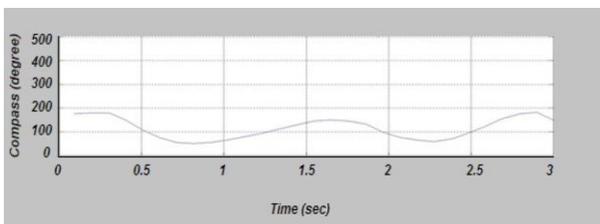


Figure 12. Change of compass's degree, when the robot is moving forward with the first control feedback.

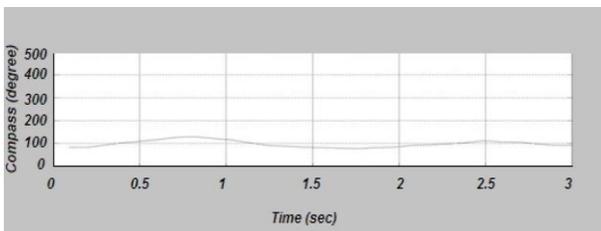


Figure 13. Change of compass's degree, when the robot is moving forward with the second control feedback.

### D. Experiments in Underwater Using Compass and Tilt Sensors

Next, we performed an underwater experiment to evaluate the simultaneous performance of both the compass sensor and the tilt sensor. The PI values were altered in order to attain the maximum balance. Due to the probable interference of the two sensor's information, a software error may occur. But at the end, after making

appropriate tuning and regulating the PI performance, the robot's performance becomes very close to the desired one (Fig. 14 and Fig. 15).

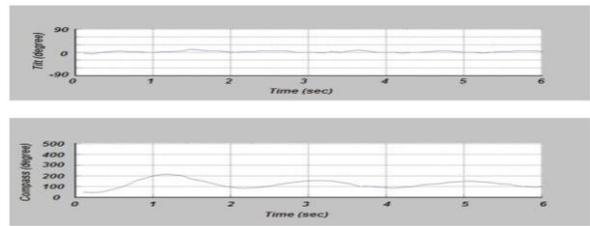


Figure 14. Change of compass and tilt's degree, when the robot is moving forward without feedback control.

Generally, by increasing the changing input values, the microcontroller helps the robot's balance by performing the controlling functions and each of the control programs prevents the other control program to run according to priority. In each cycle, some of the output values become disabled and they follow the instructions that had been sent to them before. The priority of a control function temporarily belongs to a cycle which contains the higher deviation input value which indicates the largest error in a balanced situation.

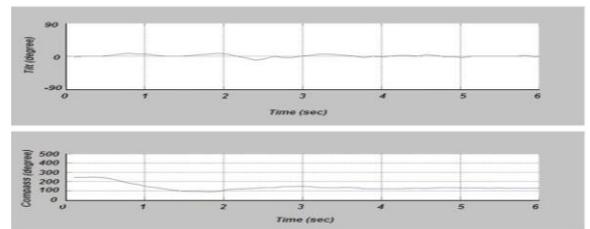


Figure 15. Change of compass and tilt's degree, when the robot is moving forward with feedback control.

### E. Experiments in Underwater Using Pressure and Tilt Sensors

For this experiment, fuzzy control in gradient sensors has been implemented implicitly. Fig. 16 represents the two sensors' performance where the robot's balance at water depth is indicated by the PI controller.

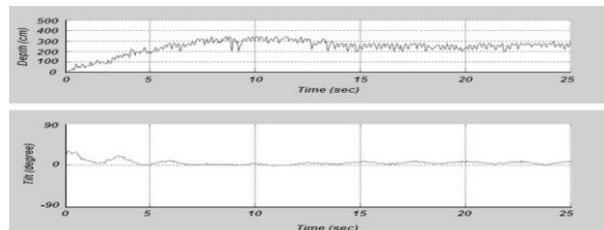


Figure 16. Change of Compass's and degree, when the robot is moving forward with the control feedback.

## VIII. CONCLUSION

In this paper, simulations and experiments were carried out to study the implementation of a relatively fast and cost-effective controller for small underwater robots. Based on fuzzy logic and PI control architecture, a new mechanical and electrical control system for autonomous underwater robot systems was designed and tested.

Furthermore, in order for the embedded robot system to efficiently interact to dynamically changing environments, six degrees of freedom have been considered for stabilized moves in both vertical and horizontal directions.

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