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PID-FUZZY Control System for Autonomous Underwater Vehicles (AUV): Highly Accurate FPGA Implementation

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Because of the linear and nonlinear variations in the operating environment, autonomous underwater vehicles (AUVs) are one of the most difficult applications. The complexity of the control algorithm should be less for real-time implementation in a field programable gate array logic (FPGA) device. In this work, a highly accurate FPGA implementation of PID-Fuzzy control strategy is proposed for an AUV operation that is extremely precise. Parameters such as weight, water density, and depth are used to perform highly efficient and accurate control for the proposed system. A type II fuzzy logic controller and accompanying proportional-integral-derivative controller are used to confine pitch and depth boundaries. The proposed design is modeled using SIMULINK software, and Verilog code is generated using hardware description language coder from MATLAB. Xilinx software is used to synthesize the Verilog code for spartan FPGA. The proposed technique improves the accuracy and reduces the response time when compared to the conventional control strategy.

Keywords: autonomous underwater vehicle (AUV), field programmable gate array (FPGA), fuzzy logic controller, PID controller, real-time implementation

INTRODUCTION

The underwater sphere-shaped robot study started in the early 1990s when the University of Hawaii developed the Omni-Directional Intelligent Navigator (ODIN), a sphere-shaped underwater robot. As a significant control strategy, questionable control enjoys the main benefit since it depends not just on a precise numerical model of the control framework, yet in addition on the effective control of the nonlinear framework. ODIN is basically utilized for environmental checking and submerged techniques with eight engines, a SONAR sensor, a pressure sensor, and a route structure that is not involved. It has solid effectiveness and is hostile to sticking execution (Chen *et al.* 2018). The inconvenience is that it is hard to guarantee great soundness and affectability of the control framework.

It is important that the final effect of such autonomous underwater robots moves precisely and easily to accomplish the ideal direction. Industrial underwater robots are generally used in industries for welding, grinding, and painting purposes. The widespread acceptance of traditional straight PID regulators in mechanical circumstances is characterized by their simplicity of design and flawless implementation in practical applications (Abdul Kadir *et al.* 2018). The output signal is measured continuously to recalculate the required correction for the movement of the underwater robot (Tao *et al.* 2015). The movement control is a

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*Corresponding author: devjanibhattacharya2016@gmail.com fundamental innovation of a submerged robot. The security control of a submerged robot is critical. The control of submerged robots incorporates plenty of perspectives like machine vision, direction following, data combination, climate displaying, liquid mechanics investigation, shortcoming analysis, obstruction shirking, route, correspondence, and so forth; a submerged circular robot is not just an emphatically nonlinear framework – yet, in addition, a multi-input/multi-yield framework. In the meantime, a submerged robot can be helpless to the vulnerability of sea flow. Along these lines, it is difficult to get steady development control in the submerged environment. Right when experts picked some standard techniques, for instance, traditional PID control computation to design the submerged robot controller, the typical influence in view of the counter-irritation limit isn't adequate. Researchers have encouraged a lot of new procedures; at this point, a part of the utilization of control methodologies was difficult to achieve (Dong *et al.* 2019). The majority of the submerged robot development control processes were in this stage of development, thus urging better ways to deal with these challenges in the practical application. In submerged robot control calculations, PID control, flexible control, fuzzy control, sliding mode control, neural network control, robust control, and a combination of a few control algorithms are now employed. The integration of the PID controller structure and the knowledge of the FIS specialists provide unique control characteristics in a wide variety of studies. However, not all controllers use PID controllers, and FLC is widely used and successfully applied in machine control applications. FLC was primarily used to control processes through vague linguistic descriptions (Londhe *et al.* 2017).

Nonetheless, PID regulators uncover impediments when frameworks have nonlinearities or vulnerabilities. Furthermore, the exhibition of the regulators has a high reliance on the tuning of boundaries (Chen *et al.* 2016). For locating the lawful arrangement of the regulator's limits, several methodologies have been proposed – including the Ziegler-Nichols methodology, ant colony optimization algorithm, and genetic algorithm (Bui and Kim 2006). Furthermore, intelligent controllers such as the fuzzy inference system (FIS), which incorporates human experience into control processes, have been proposed for more complex and rigorous control situations because, through their remarkable capacity, nonlinear frameworks are approximated (Kanakakis *et al.* 2004). In this work, a new technique with more flexibility and controlling AUV efficiently with less complexity is used. Also, the response time is reduced for operations. It is also suggested that an AUV's pitch and depth be controlled using a PID and fuzzy controller (Guerrero *et al.* 2019). By proposing this work, the main objectives of this system are: [a] to design a flexible controller to switch the AUV in a highly accurate manner, [b] to implement the control strategy with less complexity and should meet the condition for real-time implementation, and [c] to reduce response time and increase the accuracy of the design (Javadi-Moghaddam and Bagheri 2010).

Previously, several works have been proposed to perform the underwater vehicle control process. In this section, detailed information about some of the previous techniques is described. All the previous works are targeted to increase accuracy, but the complexity of the system is one of the important factors for real-time implementation. Detailed information about the previous techniques is discussed below.

For double latency for nonlinear systems, Qian *et al.* (2020) presented a versatile neuro-fuzzy PID regulator based on twin delayed deep deterministic policy gradients (TD3) calculation. The strategy was compared to a linear PID controller on a trolley pole system in a simulated environment, demonstrating the usefulness and generalizability of a specific technology. The controller combines the benefits of both FIS and PID controllers in terms of control and optimizes settings using a reinforcement learning mechanism (Teo *et al.* 2012). In the context of reinforcement learning, embedding previous information into the actor network's fuzzy PID controller lessens the complexity of learning during the training phase. The suggested method was tested in a simulation environment with a cart-pole system and compared to a linear PID controller, demonstrating the new methodology's resilience and generality (Shi *et al.* 2020).

The fuzzy logic PID control system was created to make switching between pre-programmed sets of financing dynamics as simple as possible, resulting in a stable and easy-to-handle AUV. A fuzzy logic PID-based control system was developed to successfully switch between sets of equilibrium kinematics, resulting in a stable and highly flexible system. Fins are simulated using computational fluid dynamics analysis and test results as part of a 6-DOF vehicle model. At the vehicle level, the benefits and drawbacks of both strategies are analyzed. The results of the simulation reveal that a range of strategies can be used to increase system performance (Geder *et al.* 2008).

According to Majid and Arshad (2015), a regular proportional-integral-derivative (PID) controller is suggested, which uses three equal fusible self-tuning PID regulators to follow the automatic speaker verification's (ASV) optimum position and angular direction. To increase the PID controller's responsiveness, an FIS is utilized to adjust the controller settings depending on a set of control rules. Three parallel fuzzy self-adaptive PID controllers in the surge, sway, and yaw axes track the

ASV's target location and angular orientation. For jumps, yaw rates, and speeds, it is widely used in current control frameworks. The fuzzy-PID controller outperforms the standard PID controller in reenactment tests. This helps with settling time development and control signal overshoot minimization.

In this section, detailed information about the previous techniques has been explained. Here, more works have been proposed to control AUV using various strategies. All methods have advantages and disadvantages based on the parameter such as accuracy, complexity, response time, *etc.* In the next section, detailed information about the proposed technique is explained.

Optimized design of pid-fuzzy control system for autonomous underwater vehicles

Figure 1 depicts a block diagram for the suggested technique. Sensor parameters such as depth of seabed, water density, pH of water, and the weight of AUV are the input parameters. These parameter values are normalized and given to the PID controller for controlling the pitch and depth values for the AUV. Two sensors are used in this proposed method: one is a depth sensor, and the other is a pitch sensor. The depth sensor determines the depth of the seafloor, whereas the pitch sensor determines the direction of movement.

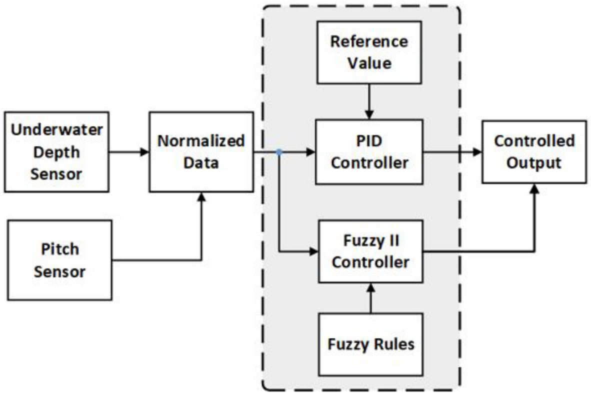

Figure 1. The proposed method's block diagram.

Depth and pitch control

The PID controller is used to monitor the vehicle's velocity and depth. When the two engines push, the two separate mobile floats equally in the same rotating direction, and the float-shift mechanism system supplies pitch torque to an AUV (Hu *et al.* 2013). When the engine's drive floats equally in the opposite rotating direction, the float-shift mechanism technology gives roll torque to the AUV. The combination of three drives sends pitch and roll torque to AUV. The scheme's structure is straightforward and simple to implement. The restored moment formed between the center of buoyancy and the center of gravity is easy to quantify and analyze. It's simple to make the device and change the position of the floats to control the center of buoyancy. The center of the vehicle's mass is where the body-fixed coordinating frame is located. The second law of Newton describes translational motion.

$$\mathrm{F} = \mathrm{ma} \tag{1}$$

where the vehicle's mass is "m," and "a" is the acceleration of the vehicle's center of mass. The Euler equation governs the rotational motion of the vehicle.

$$\mathrm{M_c} = \mathrm{I_c}\omega + \omega \times \mathrm{I_c} \tag{2}$$

External forces and moments include gravity, propulsive control, buoyancy, and hydrodynamic forces (F and $\mathrm{M_c}$) [19]. The AUV's six degrees of freedom equation of motion can be written in terms of body-fixed coordinates using Newton's Euler equation.

$$\begin{aligned} &\mathrm{l}[\mathrm{n} - \mathrm{vr} + \mathrm{xq} - \mathrm{y_g}\,(\mathrm{q}^2 + \mathrm{s}^2) + \mathrm{x_g}\,(\mathrm{pq} - \mathrm{s}) \\ &+ \mathrm{k_g}\,(\mathrm{pr} + \mathrm{q})] = \textstyle\sum \mathrm{x_{exv}} \end{aligned} \tag{3}$$

Variables v, x, p, q, and $\mathrm{y_g}$ are assumed negligible, whereas $\mathrm{k_g}$ is almost kept constant in the pitch channel maneuver. Table 1 shows the parameters used for pitch control with their corresponding values, where $\mathrm{l_{xxp}}$ have the value of 2.8 $\mathrm{Kgm^2}$, $\mathrm{z_{ext}}$ have the value of 3.45 $\mathrm{Kgm^2/s}$, and these values are used to calculate the rotational motion of the vehicle. The equation of motion for the pitch controller in terms of $\mathrm{z_g}$, q, and $\mathrm{y_g}$ can be summarized as follows:

$$\begin{aligned} &\mathrm{l_{xxp}} + (\mathrm{l_{zz}} - \mathrm{l_{yy}})\mathrm{qr} + \mathrm{n}[\mathrm{y_g}\,(\mathrm{w} - \mathrm{uq} + \mathrm{vp}) \\ &- \mathrm{z_g}(\mathrm{v} - \mathrm{wp} + \mathrm{ur})] = \textstyle\sum \mathrm{z_{ext}} \end{aligned} \tag{4}$$

Table 1. Parameters used for pitch control.

Parameter	$\mathrm{I_{xxp}}$	$\mathrm{k_g}$	$\mathrm{z_g}$	$\mathrm{z_{ext}}$
Value	2.8	–4.5	–5.96	3.45
Units	$\mathrm{Kgm^2}$	$\mathrm{Kgm^2}$	$\mathrm{Kgm^2}$	$\mathrm{Kgm^2/s}$

PID Controller-Based Depth Control

A simple algorithm with strong robustness has been commonly used in fields as one of the earliest control algorithm technologies of PID. Nowadays, the vast majority of PID controllers are available. PID can achieve good adjustment by integral and differential control propulsions of the three control parameters. For the proposed cycle, which comprises an error calculation unit, Figure 2 shows the depth control utilizing the PID regulator, and the depth set point (the depth set point is the particular distance between the ocean bed and submerged vehicle, and its minimum value maybe 0.5 km) and is given as an input to get the controlled output from PID.

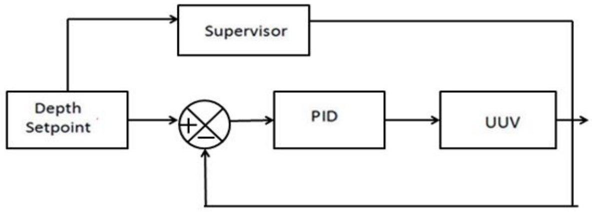

Figure 2. Depth control using the PID controller.

The PID controller is used to monitor the vehicle's velocity and depth. A fundamental PID regulator is a control device that utilizes input that is usually utilized in mechanical control frameworks and incorporates continuously modulated control in a number of other applications (Nag *et al.* 2013). The difference between a depth setpoint and the computed process variable M(t) is calculated by a PID controller as an error value e(t). It then uses proportional, integral, and derivative terms to fix the inaccuracy (denoted P, I, and D, respectively). In practice, it uses pinpoint accuracy and reactivity to automatically rectify a control function. The controller's PID algorithm returns the predicted speed to the intended speed by boosting the engine's power output with little delay and overrun (Liang *et al.* 2006).

$$M\,(t) = Lp\,e(t) + Li\int_0^t e(t')dt' + Ld\frac{de(t)}{dt} \qquad (5)$$

where M(t) is the output power signal, Li is the integral gain parameter, Lp is the proportional gain parameter, and Ld is the derivative gain parameter. In order to improve the overall performance of the PID controller, these three parameters will be modified using the uncertain inference approach (Ishaque *et al.* 2010). Before Lp can start the auto-tuning method, the initial values for each PID parameter must be computed; $e(t)$ is the error signal, and Lp, Li, Ld are the gain coefficients of the proportional, integral, and derivative gains respectively.

$$\omega\_s\,(t) = Lp(X(t) - X(d)) + L\_\theta \times \theta\,(t) + Lq \times q\,(t) \qquad (6)$$

The elevator angle is ω_s (t), and the vehicle depth in the desired trajectory is X(d), θ(t) is the pitch angle generated by the depth controller, and q(t) is the flow rate (Wang *et al.* 2020). Table 2 shows the parameter used for in-depth control and pitch control, with the corresponding values in units such as elevator angle at 120 degrees for control of the pitch, with the trajectory angle at 94 degrees.

Table 2. Parameters used for in-depth control.

Parameter	**ω_s (t)**	**X** (d)	**Θ** (t)	**q** (t)
Value	120	18	94	82
Units	(°)	Km^2	(°)	(°)

Pitch Control Using A Type II Fuzzy Predictor

Type II fuzzy sets are frequently used in rule-based fuzzy logic systems (FLS) because they can describe uncertainty, but Type I fuzzy sets cannot. The membership function of the enigmatic set of type I has nothing to do with uncertainty, which appears to be at odds with the use of the term fuzzy, which indicates a high level of uncertainty. A Type II FLS is depicted in Figure 3. By allowing us to integrate membership function uncertainty in fuzzy set theory, the Type II fuzzy set addresses the above concerns of the Type I fuzzy set. As the level of ambiguity decreases, goes toward decisiveness (Shi *et al.* 2017).

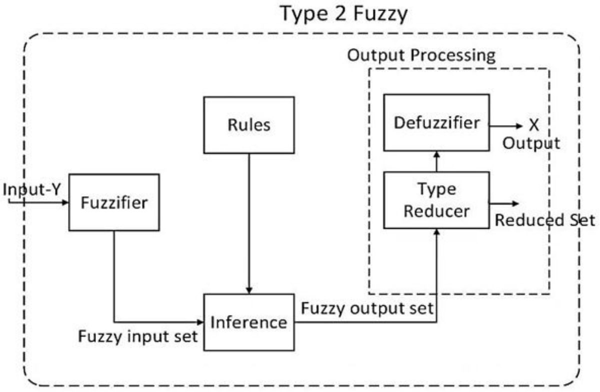

Figure 3. Type II fuzzy logic system (FLS).

Integration of FLC with PID Controller

A fuzzy logic controller (FLC) is integrated with the PID controller to track the speed of the AUV and to measure the depth and pitch of the vehicle. The block diagram for integration is shown in Figure 4. The systematic modeling of type-2 FLC is a difficult task as the output cannot be determined in a closed form because of KM-

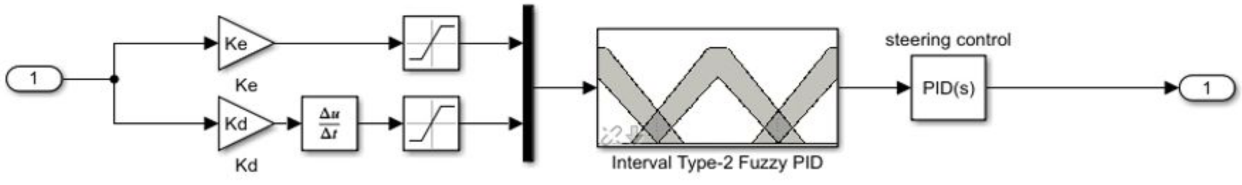

Figure 4. Integration of FLC with PID controller.

type reduction in FLC. The proposed approach will reduce the parameter dependency, which needs to be tuned to achieve desired results.

FPGA Implementation

The Spartan 6 FPGA board shown in Figure 4 is a digital device development board that includes a Xilinx Spartan 6 FPGA, 4 MB of non-volatile external memory, and a multiple I/O interface for different digital applications (Khodayari and Balochian 2015). The Xilinx Spartan 6 FPGA is a platform suitable for any sort of implementation using the latest Xilinx technologies, perfect for the creation of a new control system capable of building logic circuits without worrying about complex external interfaces (Fang *et al.* 2015). The efficiency of this board's use of energy would minimize power usage and make it important for continuous use. The RTL and Xilinx technology schematic view of the synthesized Verilog code is shown in Figure 5. Figure 5a depicts the RTL schematic, and the Xilinx Technology Schematic is shown in Figure 5b.

RESULTS AND DISCUSSION

The proposed AUV controller design uses 100, 85, and 50 for P, I, and D values, respectively. Subtracting the current output from the controlled output value yields the error value (Marvian *et al.* 2018). The design is compiled in the Spartan-6 board and verified successfully. Fuzzy rule sets are selected to implement the proposed architecture.

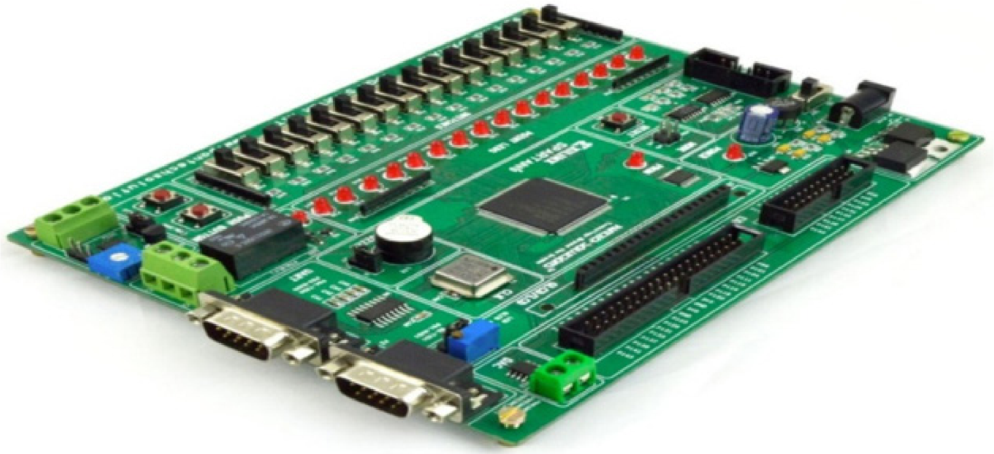

Figure 4. Xilinx Spartan 6 FPGA board.

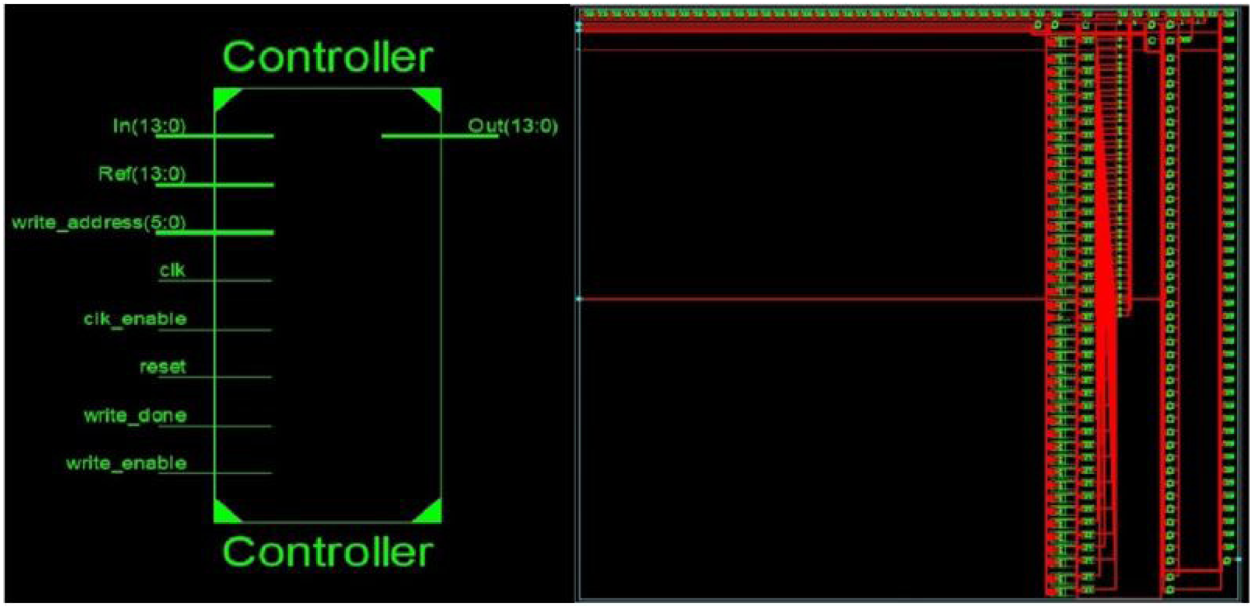

Figure 5. RTL and Xilinx technology schematic view for the synthesized Verilog code.

Also, to compile at the backend level, various floating technologies are used to determine the depth, and an underwater depth sensor is employed (Palis *et al.* 2006). The AUV pitch sensor is used with the aid of an inertial measurement unit to monitor the pitch. Simulation is performed using SIMULINK software. The response of the system is tested using the unit step function block, which is available at the Simulink library.

Table 3 compares the suggested technique to the existing techniques. The related values in Table 3 demonstrate that the proposed system outperforms existing systems.

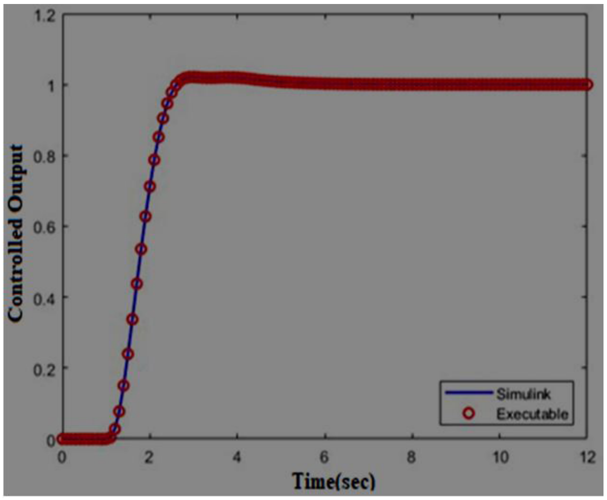

Figure 6. Response obtained for step input.

Table 3. Comparison with existing techniques.

Types of controller	PID	FUZZY	[1]	[2]	Proposed system
Error	35%	19%	63%	–	9%
Time response(s)	0.003	0.08	–	0.594	0.021

The vehicle has moved to the setpoint and held at the station for a while before moving to the next one. The response obtained for a step input is shown in Figure 6. It is based on the time corresponding to the output obtained for the input response. Figure 7a shows a Simulink model containing a plant. It is made up of a reference input that is sent to a fuzzy PID, the output of fuzzy is given as input for the plant to get the final output value (Son and Kim 2012). Figure 7b shows the Simulink model for the fuzzy PID controller. It is the model for code generation, where the graphic computing element (GCE), computing element (CE), global control unit (GCU), and control unit (CU) are gains of the controller.

Table 4 shows the device utilization summary, which is comprised of registers, buffers, and a look-up table (LUT). The total number of devices available and utilized, as well as the percentage of utilization, is observed in this table. DSP48A1s uses 74% of the device, which is the maximum in the table. Bonded IOBs show the second most utilized resource and the slice register shows the least utilization of the device. Table 5 shows the parameter used for the

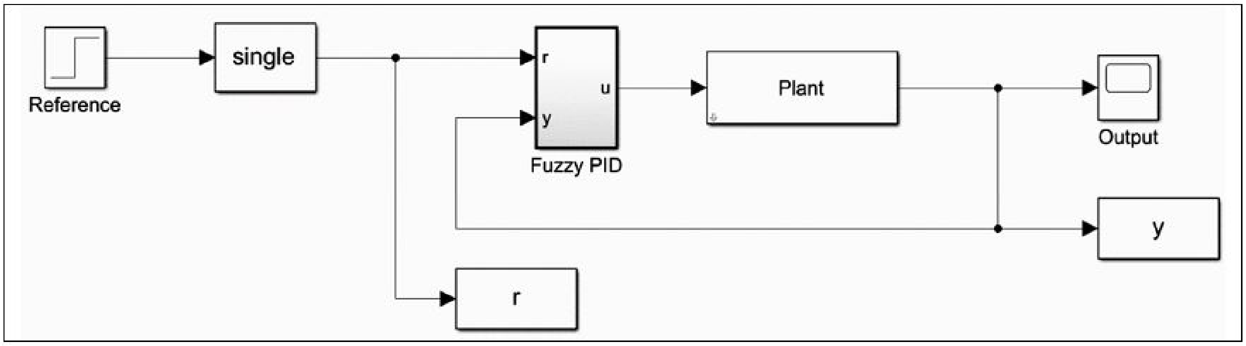

Figure7a. Simulink model with plant.

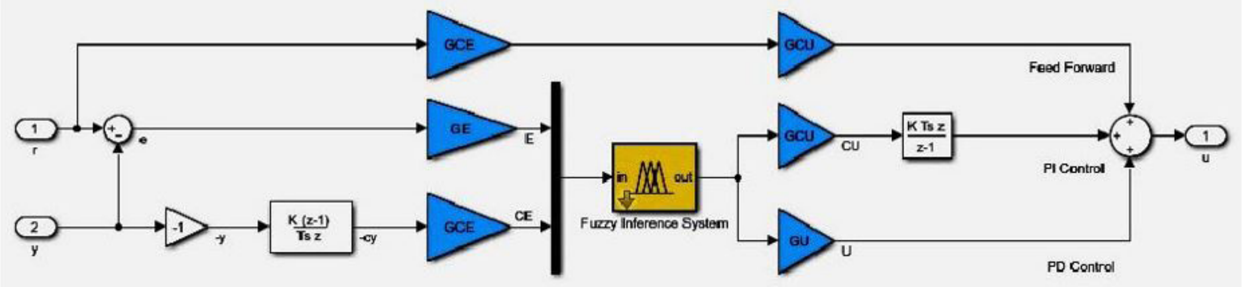

Figure 7b. Simulink model for fuzzy PID controller.

Table 4. Summary of device usage.

Utilization of logic	Quantity of slice registers	Total number of slice LUTs	Number of LUT-FF pairings that have been fully utilized	Total number of bonded IOBs	Number of BUFG/BUFGC-TRL/BUFHCEs	Number of DSP48A1s
Utilized	1842	1882	623	53	2	43
Available	55586	26298	3101	218	15	58
Percentage of utilization	3%	5%	20%	24%	5%	74%

Table 5. Parameters used for implementation.

Length of link [m]	Diameter of link [m]	Mass of link [kg]	Rated output [W]	Rated torque [N]	Rated revolution [rpm]	Resolution [pulse/rev]	Gear ratio (gear head)	Gear ratio (gearbox)
0.25	φ 0.045	1.80	19.5	4.4	50	900	1:40	1:20

implementation of the proposed method. Parameters are specified with the corresponding values in conventional units. The link diameter is given as in radius, so its φ(phi) value is 0.045.

CONCLUSION

A highly accurate FPGA implementation of PID-fuzzy control strategy for AUV for accurate operation technique to improve accuracy is suggested in this work. In the Spartan FPGA, the proposed controller architecture is implemented using Xilinx software. To provide highly precise controlled yields, the general regulator is implemented using a combination of fuzzy PID algorithms. The proposed controller is implemented in the FPGA device for testing the feasibility of a real-time application. This work increased the accuracy and reduced the response time when compared to the conventional control techniques.

CONFLICT OF INTEREST

There are no conflicts of interest declared by the authors.

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Devjani Bhattacharya and C. Puttamadappa were involved in the research design and implementation, as well as the analysis and writing of the publication.

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