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ABOUT THE JOURNAL

COMPLETE: Journal of Computer, Electronic, and Telecommunication is an official journal of Telkom University. It publishes research or review articles in Computer, Electronic, and Telecommunication technology. This journal provides a platform for research lecturers, reviewers, practitioners, industry, and observers across Indonesia and overseas to promote, share, and discuss new issues and technology development. The scope of the journal includes:

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PREFACE

Welcome to the Journal of Computer, Electronic, and Telecommunication, Vol. 6, Issue No. 1. It is my privilege and pleasure to present the sixth volume of this peer-reviewed journal under Telkom University. This journal aims to accommodate the results of research publications through national and worldwide journals as part of continuous improvement.

As the chairman of COMPLETE, I would like to thank many people who supported this journal, especially Research and Community Service Units (LPPM). Furthermore, as the editor-in-chief, I would like to extend my sincere thanks to all members of the editorial and the advisory boards from Telkom University, whose service, dedication, and commitment have made the creation of this journal possible. We work together to improve the quality and excellence of articles published continuously.

We hope that COMPLETE could deliver valuable and interesting information and stimulate further research to the worldwide telecommunications, electrical, and computer engineering communities.

Surabaya, July 2025

Editor-In-Chief of Journal

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Article

Water Monitoring and Control System in Krofta System with *Fuzzy* Logic Method

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Abstract: Krofta is a water purification technology widely used in industries, particularly in paper and tissue manufacturing. In this study, a *Fuzzy* logic-based control method is applied to the input and output parameters of the system. The developed system utilizes a Sugeno *Fuzzy* system with three main inputs: TSS (Total Suspended Solids), pH, and temperature, and an output parameter in the form of PWM (Pulse Width Modulation) to control the booster pump for injecting chemicals to maintain water quality. The water purification process involves the injection of a chemical agent, specifically a fennopol solution, which is pumped by a booster pump. The booster pump is controlled by an AC Dimmer module driver based on the PWM output generated by the *Fuzzy* method. During this process, data from each parameter is recorded in real-time using a MySQL database and displayed via a *web interface*, with both components interconnected. Based on the research findings, the accuracy results for the sensors are as follows: the temperature sensor has an average *error* of 2.736%, the pH sensor has an average *error* of 1.742%, and the TSS sensor has an average *error* of 4.10%. For the PWM parameter, the system achieves highly accurate PWM values, effectively optimizing the tested water parameters. In conclusion, the Sugeno *Fuzzy* method demonstrates an average accuracy of 97.1% in monitoring and controlling the system to support decision-making processes.

Keywords: Krofta System, Total Suspended Solid (TSS), Water pH, Water Temperature, *Fuzzy* Logic

1. Introduction

Tissue has become a primary necessity in daily life due to its practicality compared to handkerchiefs, which require washing after use [1]. Made from natural fibers or recycled paper, tissue serves various purposes, such as cleaning hands, faces, and sanitation needs. Its high demand has driven industries to produce diverse tissue types tailored for specific uses. An essential component in tissue production is water, utilized at various stages, including pulp processing, sheet formation, and cleaning production components like felt and wire. Felt and wire are critical elements in tissue-making machines. Felt absorbs water from wet tissue sheets, while wire serves as a platform for forming wet pulp into sheets [2]. Maintaining their cleanliness is crucial to ensure optimal production, which is achieved using high-pressure water sprayed through specialized nozzles. This water often originates from recycled production water, such as white water, processed into clarified water using the Krofta system. The Krofta system, or Dissolved Air Flotation (DAF), is a wastewater treatment technology that separates solid particles from water, enabling its reuse in production processes.

Water plays a vital role in industrial processes, particularly in maintaining quality standards and supporting recycling systems. Monitoring parameters like pH, Total Suspended Solids (TSS), and temperature is essential to ensure water quality.

Recent studies have explored innovative methods to enhance water quality management, integrating Internet of Things (IoT) and *Fuzzy* Logic. [3] developed a system to control pH and temperature for ornamental fish farming using *fuzzy* logic. Their system utilized sensors to detect pH and temperature, processed by a *Fuzzy* Sugeno Method with membership functions for temperature (cold, normal, hot) and pH (highly acidic to highly alkaline). Outputs were managed via actuators like motor pumps, with results displayed on an LCD and web-based monitoring.

Similarly, [4] designed a water quality monitoring system using IoT to control parameters like pH, Total Dissolved Solids (TDS), and TSS. They employed *fuzzy* logic to analyze data and manage water quality effectively. These studies highlight the effectiveness of integrating *fuzzy* logic and IoT for monitoring and controlling water quality in industrial applications. Fuzzy logic is the chosen method because the data is constantly changing or uncertain, as the three parameters fluctuate over time and with water quality. It also offers ease of implementation and operation and can process multiple variables. Given the importance of water recycling in tissue manufacturing, accurate monitoring and control of parameters such as TSS, pH, and temperature in the Krofta system are crucial. This study aims to develop a *fuzzy* logic-based control system to optimize water recycling processes, enhance efficiency, and minimize liquid waste in the tissue manufacturing industry.

2. Materials and Methods

The study described focuses on developing a system for control and monitoring KROFTA system with Logic *Fuzzy*. The method used is using sugeno *fuzzy* logic. This method will be a system that will get input from three sensors and the system output will regulate the water flow speed of the booster pump and the sensor readings will be displayed on the LCD screen. The results of sensor readings and booster pump settings will be recorded because it uses a realtime database, namely MySQL and the user interface will use a web url., as illustrated in Figure 1, outlines the key components and processes involved in the application's functionality.

The sensors used are to monitor the parameters of temperature, pH, and TSS. The sensor used is waterproof and in accordance with the scale of small projects that can support ESP32 microcontrollers. The sensors used on average already have drivers to accommodate sending analog to digital converting data, the sensors used are DS18B20 temperature sensors, DFRobot Turbidity Sensor V1 sensors, and PH-4520C water pH sensors. This ensures that the input data is of sufficient quality for accurate detection. Using Sugeno *fuzzy* because the system has advantage of how many input and output data. this method also has advantages for the control and supervision process [5]. the advantages include: using linear or constant mathematical functions, easy implementation because the output is constant, and stable performance because it does not require a complex defuzzification process. Finally, the system undergoes testing to evaluate its performance and accuracy in monitoring and controlling Krofta System under various conditions.

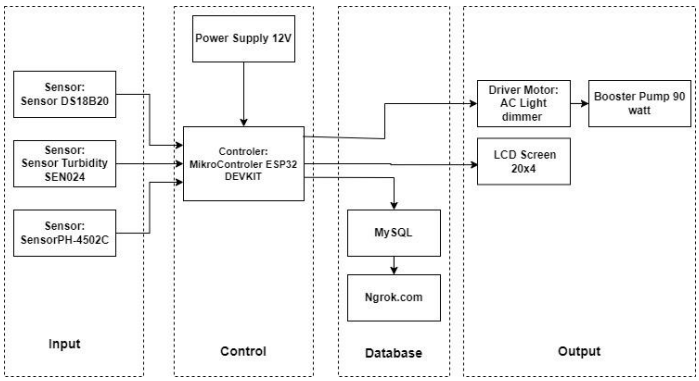


Figure 1. System Framework

In this research process, it begins by observing problems related to water parameters in the krofta system. After that, review the relevant and appropriate literature because it will be used as a reference for the research. This literature review includes an analysis of previous studies on control and monitoring process the water parameter that have been developed and tested by other researchers. After reviewing the literature used as a reference, it will be continued by analyzing the needs. This needs analysis includes methods that use the *fuzzy* sugeno method, the form of a device that can detect for monitoring and controlling, and after determining the design, namely determining the program to be created. The factors that are taken into account are the water parameters used, namely temperature, pH, and saturation level of the crofta water as well as the controlling factors for pumping the flocculant solution in the crofta system. The next step in making a mechanical design is to make a control panel that contains the sensor module and ESP 32 and determine the water pump path that will be used. in the process also calibrate the accuracy of each sensor used with the linear regression method so that the presentation of the sensor reading error is small so that the sensor can be said to be accurate and precise. also ensure the testing of the *fuzzy* method used using the *fuzzy* toolbox in the MATLAB application which is useful as a validation tool for the program whether it run properly. testing the output of esp 32, namely the regulator driver, namely AC Dimmer. During testing the data taken will be stored in real time using MySQL data and the data is displayed on the web interface with the HTTP Get Request method. This ensures that the data is recorded so that it can be monitored when the parameters change. After the field tests, the collected data is analyzed to assess the efficiency, reliability, and potential improvements for the system. Based on this analysis, the researchers draw conclusions regarding the viability of the design and its implication for monitoring and controlling the water of the Krofta System. Based on this analysis, the researchers draw conclusions about the feasibility of the design and its implications for renewable energy deployment in coastal areas and offer recommendations for future research. These conclusions may include suggestions for refining the turbine design, increasing system durability, and scaling up the technology for larger applications. Figure 2 illustrates a detailed flowchart of the entire research process.

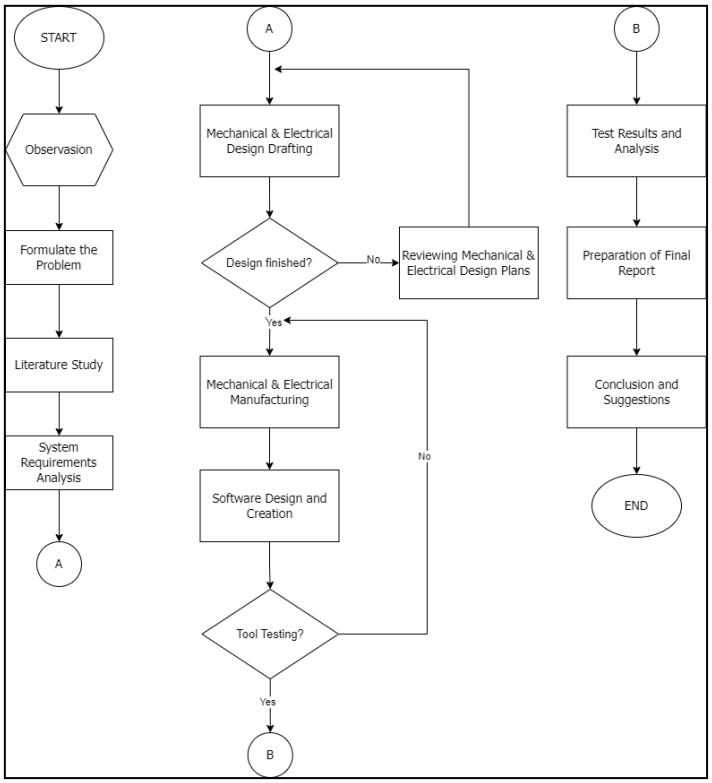


Figure 2. Flowchart Research

3. Results and Discussion

3.1. Fuzzy Methods

Fuzzy is a logic set theory that was created as a solution to the concept of values that lie between true and false [6]. In the controller process using the *Fuzzy* Logic Method, where this intelligent system is a program that can model the human thinking system (numerical variables) which is applied according to machine language (linguistic variables) in order to control the output used. In measuring 3 parameters and 1 actuator using the Sugeno *Fuzzy* logic method, the following are 4 stages of design using the Sugeno *fuzzy* logic method [7]:

- *Fuzzy* Variable & Linguistic Value determine 4 variables, in each variable the linguistic value is determined, namely:
  a. The Temperature variable is divided into 3 inputs, namely Low, Normal, and High.
  b. The pH variable is divided into 3 inputs, namely Acid, Neutral, and Base.
  c. TSS variable is divided into 3 inputs, namely Small, Medium, High.
  d. The PWM variable is divided into 3 outputs, namely Slow, Normal, High.
- *Fuzzy*fication In this process, the input data variables and output variables will be converted into *fuzzy* sets. This determination is taken from the reference value of Stock preparation in the company. In determining each linguistic value, the category of each parameter to be used can be seen in the table 1.

Table 1. Parameters form The Water

Num	Parameter	Unit	Criteria	
1	Water Temperature	°C	<30	Low
			30 - 39	Normal
			>39	High
2	Water pH		<6,3	Acidic
			6,3 - 8,2	Neutral
			>8,2	Alkaline
3	TSS (Total Suspended Solids)	Mg/L	<30	Small
			30 – 65	Optimum
			>65	Large
4	PWM	*% duty cycle*	30	Slow
			60	Medium
			80	Fast

- Rule Base (*Fuzzy* Inference) The next process is to determine *fuzzy* rules. Rules are made to present the relationship between input variables and output variables. The operator used to present the relationship between 3 input variables is the AND operator, and the mapping between output variables is IF-THEN. There are 3 variables and each variable has only 3 *fuzzy* sets, so the rules made as many as 27 rules, as shown in Table 2.

Table 2. Rule Base for *Fuzzy* Logic

Num	Variable			
	Input			Output
	Temperature	pH	TSS	PWM
1	Low	Acidic	Small	Slow
2	Low	Acidic	Optimum	Slow
3	Low	Acidic	Large	Slow
4	Low	Neutral	Small	Slow
5	Low	Neutral	Optimum	Medium
6	Low	Neutral	Large	Fast
7	Low	Alkaline	Small	Medium
8	Low	Alkaline	Optimum	Medium
9	Low	Alkaline	Slow	Slow
10	Normal	Acidic	Small	Medium
11	Normal	Acidic	Optimum	Slow
12	Normal	Acidic	Large	Medium
13	Normal	Neutral	Small	Fast
14	Normal	Neutral	Optimum	Slow
15	Normal	Neutral	Large	Fast
16	Normal	Alkaline	Small	Medium
17	Normal	Alkaline	Optimum	Medium
18	Normal	Alkaline	Large	Pelan
19	High	Acidic	Small	Medium
20	High	Acidic	Optimum	Medium
21	High	Acidic	Large	Slow
22	High	Neutral	Small	Medium
23	High	Neutral	Optimum	Medium
24	High	Neutral	Large	Fast
25	High	Alkaline	Small	Medium
26	High	Alkaline	Optimum	Slow
27	High	Alkaline	Large	Slow

- Defuzzification is a *fuzzy* set of *fuzzy* rule composition results. Also, Defuzzification is the process of converting linguistic output into numerical data [8]. Meanwhile, the output result issued is a numerical number in the domain of the *fuzzy* set itself. using Sugeno *fuzzy* logic, the defuzzification used is the average method (Weight Average).

$$z = \frac{\sum_{i=1}^{n} W_i Z_i}{\sum_{i=1}^{n} W_i} \quad (1)$$

Explanation:

- Z is the crisp value (firm value) of the defuzzification result.
- W_i is the membership degree or weight of the i-th rule. This weight is usually derived from *fuzzy* inference and indicates how much the rule is satisfied.
- Z_i is the output of the i-th rule. This output can be a constant value or a linear function like $Z_i = a_i X + b_i y + c_i$
- n is the number of *fuzzy* rules.

3.2. Mechanical Design

Mechanical design for the placement of temperature, pH and turbidity (TSS) sensors will be installed through a sample tank that is already available and sourced from the Krofta tank. The actuator used, the booster pump, will pump the chemical agent to the krofta system in the whitewater tank. In addition, the mechanical design for the controller in the work of this tool uses an electric panel box with a size of 12 cm long, 17 wide, and 20 cm high where the box will contain components according to Figure 3 and Figure 4:

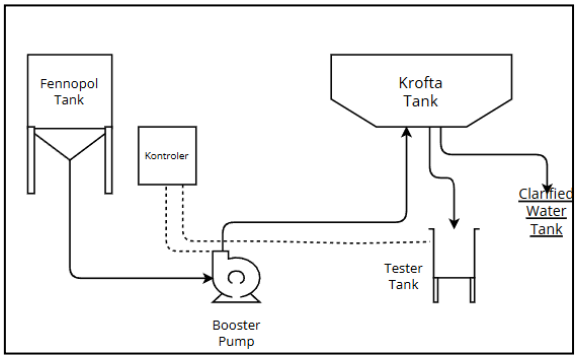


Figure 3. Sample Tank Krofta System

Figure 4. Sample Tank Krofta System

3.3. Software Design

The software design is escorted by programming the ESP32 microntroleer to be able to run the system where to read the sensor value and control the actuator as the output of the system. the program must also be able to transmit and store data in realtime. for the use of data storage systems, the use of MySQL as a data cloud system that can store the results of reading the parameters of temperature, pH, and water turbidity level (TSS). MySQL is a database system system that is widely used for web application development [9]. Using HeidiSQL application to design and manage MySQL database. HeidiSQL was chosen because of its easy interface that supports the process of creating tables, relationships, and organizing data efficiently [10]. Data from the system is sent to the server via the GET method using PHP files specifically designed to accept parameters from client devices. With this approach, integration between the hardware and the database becomes easier.

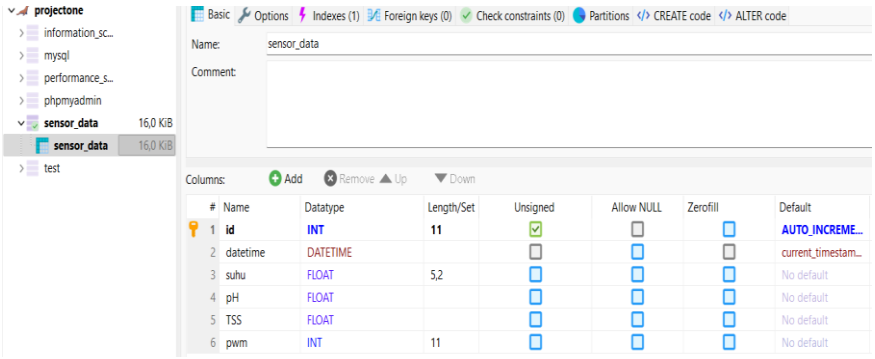


Figure 5. Table from MySQL Database

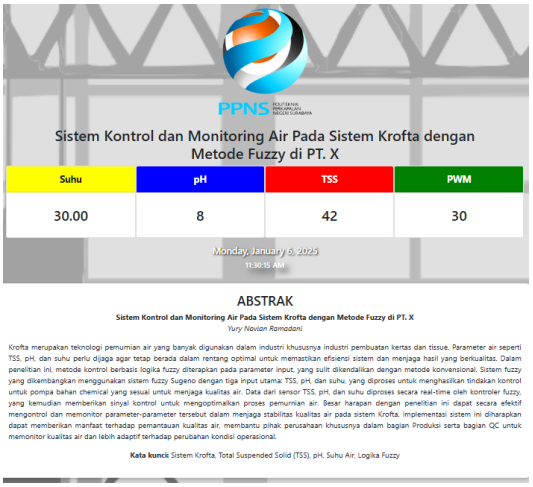


Figure 6. System view on the web

The system interface uses a web that will display the tested parameter data in real time by connecting the Arduino program with a realtime database and using ngrok.com web hosting to be able to publish. Ngrok is a platform that provides a solution that enables applications on private networks to be accessed over the internet [11]. The following is figure 6 which displays the parameters.

3.4. Sensor Testing Results

Sensor testing is essential to ensure the accuracy and reliability of water quality monitoring systems. It involves evaluating sensor performance in detecting parameters such as pH, TSS, and temperature under varying conditions. Proper testing helps optimize the system for real-time monitoring and efficient water management. This aims to evaluate the level of accuracy and determine the percentage of deviation for each component used. The test results will be compared with standard measuring instruments to assess sensor accuracy and validate its performance. The difference between the sensor measurements and the established standard will then be identified. Additionally, the percentage of deviation calculated from this comparison provides a deeper understanding of the sensor's accuracy in measuring the tested parameters.

$$\%\ Percentage\ Eerror = \frac{set\ point\ -\ Sensor\ Value}{Set\ point} \tag{2}$$

Knowing whether the DS18B20 Temperature Sensor Module, 4520c pH sensor module, and SEN024 sensor module can work properly and can display the temperature, pH, and TSS according to the program that has been made on the Arduino IDE by comparing the readings with the calibrator

tool. The test uses liquids of different temperatures to prove the reliability of the sensor readings. The liquid has 5 different set points as each reading will have an interval of 2 seconds and 10 data samples are taken. The results of the temperature sensor are shown in Table 3.

Table 3. Results of DS18B20

No	SetPoint (°C)	Measurement No.	Measured Temperature (°C)	Percentage Error (%)
1	3,7	1	3,63	4,54
		2	3,63	
		3	3,63	
		4	3,52	
		5	3,52	
		6	3,52	
		7	3,5	
		8	3,48	
		9	3,48	
		10	3,41	
2	17,2	1	17,52	2,07
		2	17,52	
		3	17,46	
		4	17,52	
		5	17,52	
		6	17,58	
		7	17,58	
		8	17,58	
		9	17,64	
		10	17,64	
3	27,2	1	27,36	0,48
		2	27,36	
		3	27,36	
		4	27,44	
		5	27,44	

No	SetPoint (°C)	Measurement No.	Measured Temperature (°C)	Percentage Error (%)
		6	27,30	
		7	27,30	
		8	27,35	
		9	27,30	
		10	27,30	
4	52,8	1	52,69	0,51
		2	52,75	
		3	52,75	
		4	52,50	
		5	52,50	
		6	52,50	
		7	52,44	
		8	52,44	
		9	52,38	
		10	52,38	
5	80,9	1	82,29	1,11
		2	81,81	
		3	81,06	
		4	81,06	
		5	80,42	
		6	80,42	
		7	79,4	
		8	79,8	
		9	79,8	
		10	79,2	
Percentage Error from 5 Set Points (%)		1,742		

The DS18B20 temperature can display the temperature according to the program that has been made. This shows that the sensor can work well and in accordance with existing specifications. In the test results using the AMTAST WT-1 digital thermometer, an average error of 1.742% was obtained. The voltage required by the sensor is 5V which is taken from ESP 32. The results of the pH sensor are shown in Table 4.

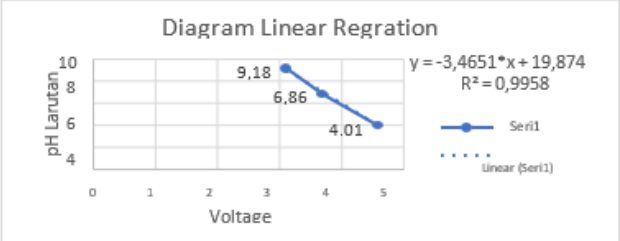
Table 4. Results of sensor 4502 pH Module

No	Setpoint for pH	Measurement No.	pH Measured	Percentage Error (%)
1	2,33	1	2,55	7,04
		2	2,48	
		3	2,55	
		4	2,47	
		5	2,4	
		6	2,45	
		7	2,38	
		8	2,55	
		9	2,56	
		10	2,55	
2	4,01	1	3,79	3,17
		2	3,83	
		3	3,89	
		4	4,0	
		5	4,24	
		6	4,19	
		7	4,09	
		8	4,02	
		9	4,16	
		10	3,92	
3	6,88	1	7,02	2,12
		2	7,01	
		3	7,07	
		4	7,15	

No	Setpoint for pH	Measurement No.	pH Measured	Percentage Error (%)
		5	7,10	
		6	7,07	
		7	6,95	
		8	6,95	
		9	6,97	
		10	6,97	
4	8,76	1	8,7	0,81
		2	8,69	
		3	8,69	
		4	8,75	
		5	8,74	
		6	8,7	
		7	8,66	
		8	8,65	
		9	8,59	
		10	8,72	
5	9,19	1	9,18	0,54
		2	9,19	
		3	9,2	
		4	9,16	
		5	9,05	
		6	9,05	
		7	9,13	
		8	9,2	
		9	9,2	
		10	9,1	
Percentage Error from 5 Set Points (%)		2,736		

Table 5. Results of Voltage from pH sensor

pH	Voltage	ADC Value
4,01	4,6	3.767
6,86	3,7	3.030
9,18	3,12	2.555



The 4520C pH module sensor can display pH in accordance with the program that has been made. This shows that the sensor can work well and in accordance with existing specifications. This is supported by using the linear regression method which gets the equation pH solution = (3.4651 * voltage) + 19.874. In the test results, the calibrator uses a pocket pHMeter PH- W2 and the sensor test results obtained an average error of 2.736%. On 5 different pH solution samples. The results of the Turbidity (TSS) sensor are shown in Table 5, Table 6, and Table 7.

Table 6. Results of sensor SEN024 DFRobot

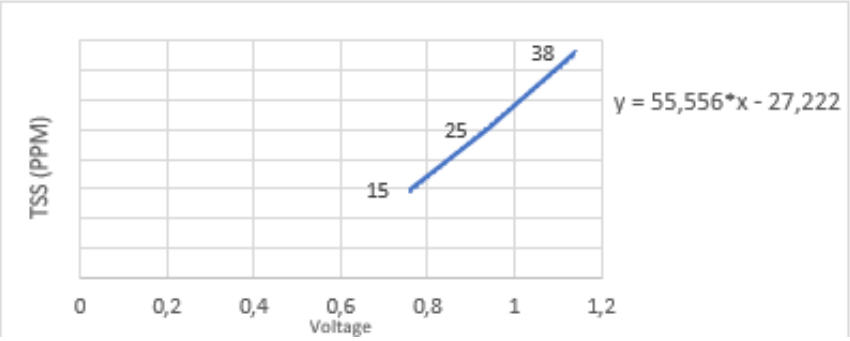
No	Setpoint for TSS (PPM)	Measurement No.	Measured TSS (PPM)	Percentage Error Every Setpoints (%)
1	15	1	15,8	2,12
		2	15,9	
		3	15,4	
		4	16,1	
		5	16,2	
		6	14,9	
		7	14,3	
		8	15,1	
		9	15,4	
		10	14,8	
2	25	1	26	4,36
		2	26,1	
		3	27,4	
		4	24,1	

No	Setpoint for TSS (PPM)	Measurement No.	Measured TSS (PPM)	Percentage Error Every Setpoints (%)
		5	24,7	
		6	25,4	
		7	24,8	
		8	27,5	
		9	25,3	
		10	26,8	
3	52	1	50	4,02
		2	54,4	
		3	51	
		4	54,5	
		5	52,9	
		6	55,7	
		7	53,8	
		8	54,8	
		9	54,1	
		10	50,3	
Percentage Error from 5 Set Points (%)		4,10		

The TSS sensor SEN024 DFRobot can display TSS according to the program that has been made. This shows that the sensor can work well and in accordance with the existing specifications.

Table 7. The result of ADC data readings with sensor voltage

TSS (PPM)	Voltage	ADC Value
15	0,76	622
25	0,99	770
52	1,56	1.188



This is supported by using the linear regression method which obtained the equation TSS solution 55.556*ADC voltage - 27.222). In the test results, the calibrator uses the DR900 Calorimeter and the sensor test results obtained an average error of 4.10%. In 3 different TSS solution samples.

3.5. Overall System Real-Time Testing

- First Experiment

In this comprehensive testing, the designed tool will be tested to see if all the designs that have been made are working according to their intended purpose. This test proves whether the tool used can control each parameter and whether it can run well to monitor and store data simultaneously, as shown in figure 7.

In this experiment, data was taken on January 12, 2025. In this experiment, the system can change the condition that originally had a High TSS (id number 130) to a TSS that had a small value (id number 139). The following is the data that was successfully saved on January 12, 2025. The image below shows the data stored in MySQL, in figure 8.

Figure 7. Sensor in the Testing Tank

dbmultisensor.tb_sensor: 151 rows total (exact)

#	id	suhu	pH	TSS	PWM	datetime
130	**130**	28,86	7,8	81,2	80	2025-01-12 10:05:43
131	**131**	28,87	7,83	81,36	80	2025-01-12 10:12:50
132	**132**	28,87	7,81	70,77	80	2025-01-12 10:19:57
133	**133**	28,87	7,74	60,28	60	2025-01-12 10:25:05
134	**134**	28,9	7,84	63,33	60	2025-01-12 10:31:11
135	**135**	28,87	7,87	54,84	60	2025-01-12 10:37:16
136	**136**	28,88	7,85	41,8	60	2025-01-12 10:43:21
137	**137**	28,87	7,82	38,94	60	2025-01-12 10:50:26
138	**138**	28,88	7,81	27,82	30	2025-01-12 10:57:36
139	**139**	28,87	7,9	25,0	30	2025-01-12 11:05:38

Figure 8. The Data from January 12, 2025

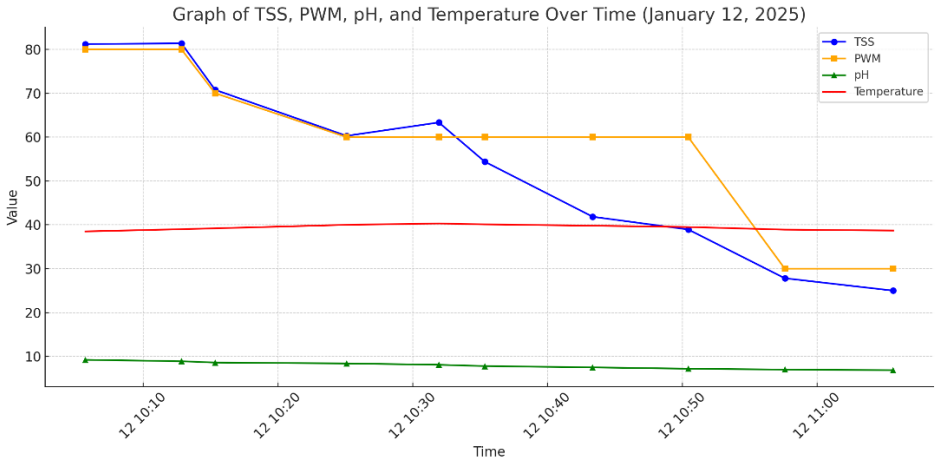


Figure 9. Graph of changes in 3 parameters

This means it takes at least 62 minutes. This depends on how cloudy the initial conditions are and the dosage of the fennopol solution dissolved, which is 1150 mg/50 L and a pressurized air injection of 0.8 bar. The booster pump will be installed after the filter pump which will filter out the dirt clumps contained in the fennopol tank.

- Second Experiment

In the experiment for second experiments, data was taken on January 27, 2025. In this experiment, the system can change conditions that originally had a slightly alkaline pH (id number 211) to an optimal pH (id number 199). This experiment was carried out for approximately 35 minutes. The pH change tends to be stable towards an optimal number, namely between 6.3 - 8.2. The use of fennopol in crofta tends not to affect changes in pH values because it is neutral. From the image below, it can be concluded that the use of fennopol for pH parameters in Krofta water does not significantly change the pH value. The pH value tends to be stable, because the nature of the chemical fennopol is neutral which will aim to lower the pH value if the pH is too high. in this experiment also for temperature parameters. In this experiment the system does not directly affect the temperature. This experiment was carried out for approximately 35 minutes. The use of this solution in krofta does not affect the temperature, because the water temperature depends on the forming process, heating by the yankee dryer, and the drying process. However, the temperature is monitored because if the water temperature is too low it will affect the production process because the water processed in the krofta system will be reused by the production section. The image figure 9 shows the data stored in MySQL. If the pH and temperature tests are displayed in the following graph figure 10.

dbmultisensor.tb_sensor: 151 rows total (exact)

#	id	suhu	pH	TSS	PWM	datetime
199	31	5,74	52,22	30	2025-01-27 07:55:42
200	27,8	5,3	55,25	30	2025-01-27 07:57:42
201	33	5,6	54,17	30	2025-01-27 07:59:41
202	31	5,96	58,11	30	2025-01-27 08:02:41
203	28	5,88	60,3	30	2025-01-27 08:05:42
204	41,2	5,88	60,87	60	2025-01-27 08:08:42
205	42,57	6,05	44,87	60	2025-01-27 08:12:32
206	37,56	6,21	55,32	30	2025-01-27 08:16:42
207	36,89	5,982	48,28	30	2025-01-27 08:19:40
208	34,74	6,44	36,3	30	2025-01-27 08:22:42
209	30,5	7,11	40,37	30	2025-01-27 08:25:47
210	30.9	7.368	40.65	30	2025-01-27 08:28:47

Figure 9. The Data from January 27, 2025

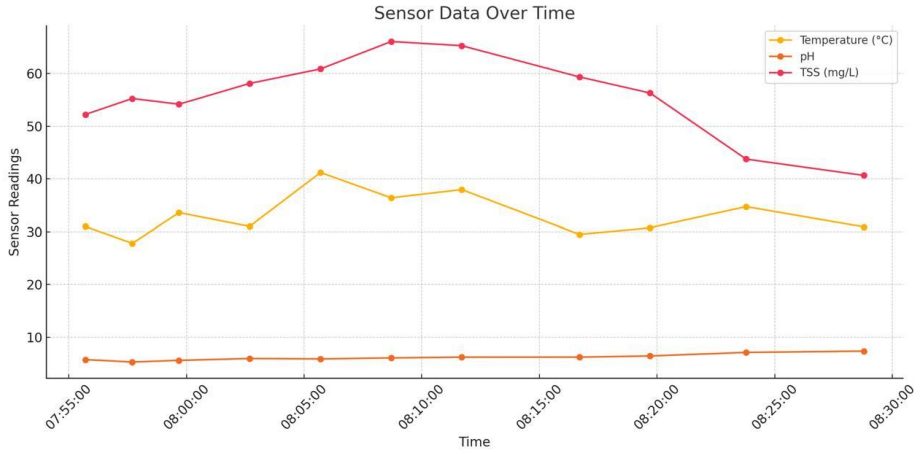


Figure 10. The Graphic of pH and Temperature

4. Conclusions

This research developed an application called " Water Monitoring and Control System in Krofta System with *Fuzzy* Logic Method" system offers use fuzzy logic methods for to handle data that is uncertain or cannot be stated clearly. The application demonstrated an average accuracy under 6% of error on 10 trials in each different parameter, indicating its potential to facilitate and expedite the counting process for the company. However, despite the relatively high values of precision, there is always a difference in readings with the calibrator tool used in the system, as well as limited motor control by only using a 90 watt booster pump. To achieve a better balance, adjusting the detection threshold or retraining the model with a larger dataset that encompasses diverse environmental conditions could be considered. Integrating this application into actual kofta system operations has the potential to enhance both efficiency and accuracy in the monitoring and controlling of krofta system.

However, it is essential to consider various challenges, including technical, operational, and user adoption aspects. It is crucial to implement technical adjustments such as improving dataset quality, utilizing superior hardware, optimizing models, and providing user training to ensure that the application functions efficiently and effectively in real-world conditions. Future work may focus on enhancing model performance through improvements in types of sensors, the use of interfaces that

can accommodate convenience, the use of pumps with greater power and can certainly be applied to the entire production system of the company.

References

1. Jangga, Saparuddin Latu, and Surya Syarifuddin. 2022. "Penyuluhan Dampak Klorin Terhadap Kesehatan Dan Cara Pemeriksaannya Di Wilayah Desa Parangbaddo Kecamatan Polongbangkeng Utara Kabupaten Takalar." JPM Jurnal Pengabdian Mandiri 1(9)
2. Ismayana, Andes, Tyara Puspaningrum, Mia Putri, and Nastiti Indrasti. 2022. "Kajian Implementasi Peluang Produksi Bersih Pada Industri Kertas Sack Kraft Pt X." Jurnal Teknologi Industri Pertanian 74–83. doi: 10.24961/j.tek.ind.pert.2022.32.1.74.
3. Putra, Andi, Slamet Budiprayitno, and Lucky Putri Rahayu. 2021. "Perancangan Sistem Kontrol PH Dan Suhu Air Menggunakan Metode Fuzzy Dan Terintegrasi Dengan Internet of Things (IoT) Pada Budidaya Ikan Hias." Jurnal TeknikI TS 10(2).
4. Matondang, Rosihan Anwar, Pausan Lubis, and Herri Trisna Frianto. 2022. "Rancang Bangun Water Treatment Sistem Pemantau Kualitas Air Berbasis Internet Of Things (IoT)." Konferensi Nasional Sosial Dan Engineering Politeknik Negeri Medan Tahun 2022.
5. Anistyasari, Yeni, and Reiza Mustika Noer. 2020. Logika Fuzzy Untuk Sistem Rekomendasi Peminatan Siswa. Vol. 2. Surabaya.
6. Wahyuni, Indah. 2021. Logika Fuzzy Tahani (Teori Dan Implementasi). 1st ed. Sleman: KamjoyoPress.
7. Amni, Destra. 2023. "Penerapan Metode Fuzzy Mamdani Pada Pemilihan Bidang Pekerjaan Sesuai Kompetensi (Studi Kasus Di Atak Kerinci)." Jurnal SIMTIKA 6(2).
8. Rachmawati, Indira Dwi, Puput Wanarti Rusimamto, and Muhammad Syariffuddien Zuhrie. 2020. Perancangan Dan Implementasi Fuzzy Logic Control Untuk Pengaturan Kestabilan Gerak Pada Two Wheels Self Balancing Robot Berbasis Arduino Uno.
9. Bahri, Syaiful. 2020. "Rancang Bangun Sistem Informasi Berbasis Web Pada Teaching Factory Bakery Smk Putra Anda Binjai." 8(3).
10. Budi Prasetya, Arifin, Rifki Ridho Dwi Saputro, and Muhammad Ridwan Arif Cahyono. 2022. "Rancang Bangun Sistem Scanner Dan Aplikasi Monitoring Tire Hasil Check Di Area Karantina OEM." Jurnal Instrumentasi Dan Teknologi Informatika (JITI) 3(2).
11. Wijaya, Gautama, Tony Tan, Stefanus Eko Prasetyo, and Sun Pho. 2024. "Analisis Perbandingan VPN Tunnel Antara Ngrok Edge Cloud vs Public IP Address Menggunakan Open VPN." Conference on Management, Business, Innovation, Education and Social Science 4(1).

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Article

Power Factor Correction on 500W Inverter Microcontroller-Base Using Particle Swarm Optimization Method

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Abstract: This research explores the design and evaluation of an inverter system incorporating the Particle Swarm Optimization (PSO) method to enhance power factor efficiency. The study investigates the inverter's performance across resistive loads (40W and 100W lamps), inductive loads (40W fan and 200W blenders), and a combination of resistive-inductive loads, both with and without PSO-based Power Factor Correction (PFC). By optimizing the phase difference between voltage and current, the PSO algorithm aims to maintain a power factor close to the industry standard of 0.85 or higher. The findings indicate that resistive loads consistently sustain a power factor of 1.00, while inductive loads benefit significantly from PSO implementation. The 40W inductive fan, initially operating at 0.55, improved to 0.57 – 0.60, whereas the 200W inductive blender increased from 0.90 to 0.98. Similarly, mixed resistive-inductive loads showed an enhancement from 0.89 to 0.99, emphasizing PSO's role in improving power efficiency. The study recorded a total power factor improvement of 0.36, with an average increase of 0.0144 per test case, confirming PSO's effectiveness in reducing reactive power losses and optimizing energy conversion. These results highlight the potential of PSO-based control strategies in enhancing power quality, stabilizing inverter performance, and improving energy efficiency, particularly in applications where inductive loads are predominant. The research contributes to the development of intelligent inverter systems that offer greater reliability, cost-effectiveness, and energy savings for residential and industrial power applications.

Keywords: Inverter; Power Factor Correction; Particle Swarm Optimization;

1. Introduction

The use of electrical energy currently plays an important role in everyday life, both on a large scale (industry) and small scale (homes). Residential houses need electrical energy as the main source to operate every electrical load. Residential houses usually have two types of loads, namely inductive and resistive loads. One of the supporting equipment that can protect various electrical loads from interference is an inverter, this tool functions as a stabilizer against interference and a backup power source [1]. Inverters play a very important role as one of the electricity supply devices at home as emergency power when the electricity goes out [2][3]. Inverters can be used with unidirectional power sources such as batteries, solar panel batteries, and other unidirectional power sources. Inverters that produce sinusoidal waves have a positive impact on power factor [5]. In addition, it can help optimize energy use, power losses, and improve power efficiency [6-9].

Power efficiency issues related to AC power in the form of voltage, current, and frequency can result in wasted energy and shorten battery/accu life [10-12]. The minimum value standard for the

power factor or power factor set by PLN based on SPLN 70-1 regulations is > 0.85[13]. A power factor of less than 0.85 is an indication of low power efficiency at the inverter output. Low power efficiency at the inverter output is caused when the electrical load power is close to the inverter capacity. This is due to the absence of Power Factor Correction (PFC) to improve power efficiency in various power efficiency problems in AC loads.

PFC can be used to optimize inductive, resistive and capacitive loads. The PFC system is made using inductive and resistive load simulations, referring to the accumulation of residential load characteristics. It takes a PFC that is able to provide capacitive and inductive compensation that can work to optimize the power factor under inductive and capacitive load conditions [14]. As for the advantages of using PFC, namely PFC as a power factor improvement tool and can also improve the voltage of the electrical system in residential homes.

Based on the problems from the background, the author intends to make a research entitled: 'Implementation of Power Factor Correction on Microcontroller-Based 500W Inverter Using Particle Swarm Optimization Method'. The planning of making an inverter circuit with PFC is to increase the power efficiency of the inverter output [15]. The PSO method is used to optimize the inverter output when using the accumulator/accu voltage input [16]. The results of this research are expected to be used as emergency power in residential homes [17].

2. Materials and Methods

2.1. Block Diagram

The research concept is used as a reference or foundation for the author to complete his research. The focus in this research is the implementation of PFC on a 500W inverter to improve the power factor value to approach the standard 0.85 or 1 The block diagram can be seen on Figure 1. The source used to test the inverter with power factor correction is accu /aki. Accu/aki is used in the hope that this research can be applied to residential homes as emergency power.

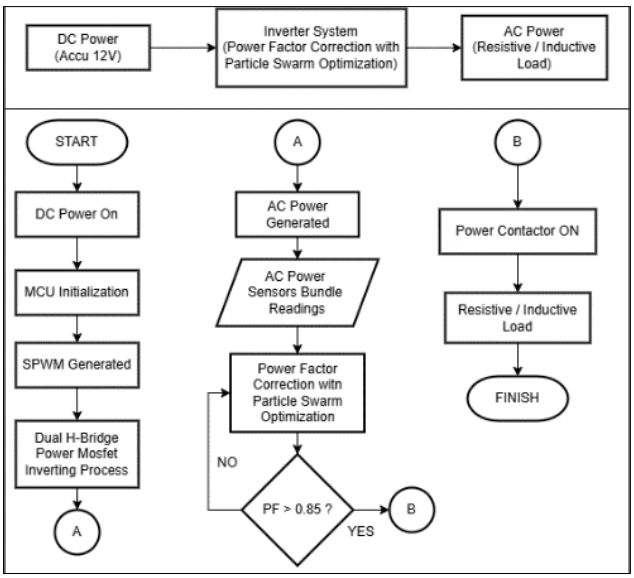


Figure 1. Inverter System Block Diagram.

2.2. Inverter System Hardware Planning

Hardware planning is made with the aim of knowing the layout of the components to be used and preparing the equipment needed in conducting this research. In addition, the planning of this inverter system is based on a block diagram Figure 1.

Figure 2(a) and Figure 2(b) are the design plans of the inverter system that will be built in this study. The panel box as the inverter cover is 40cm x 50cm x 20cm. The panel box has a selector switch that functions as a switch to run and turn off the inverter system. The panel box is also equipped with 2 green indicator lights when the inverter system is running and a red light when the inverter has a disturbance. In addition, the inverter system panel box is also equipped with an LCD display to view the parameter values generated by the inverter system such as input voltage, input current, input power, MOSFET temperature, output voltage, output current, output power, frequency, and power factor. Based on the block diagram and design planning of the inverter system, the following is the electrical hardware design planning illustrated. The descriptions for Figure 2(a) and Figure 2(b) are outlined in Table 1 below:

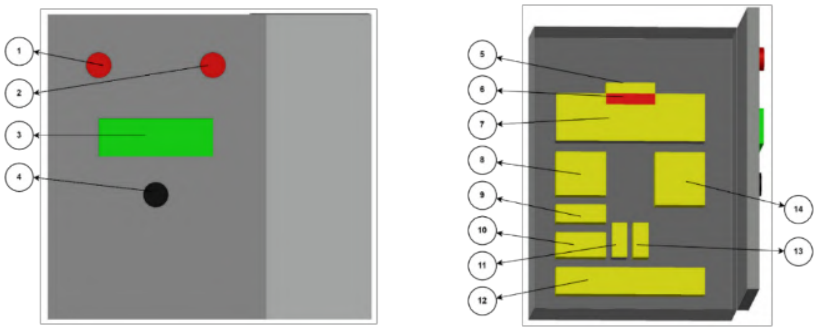


Figure 2. (a) Box Panel Hardware Planning External View, (b) Box Panel Hardware Planning Inside View

Table 1. Box Panel Numbering Description.

Instruction Number	Description
1	Indicator lamp
2	Indicator lamp
3	LCD display
4	Selector switch
5	Cooling fan
6	Temperature Sensor
7	Dual H-Bridge Power Mosfet
8	Microcontroller Unit Board
9	Voltage DC sensor
10	Voltage DC Regulator
11	Power Contactor
12	Terminal block
13	AC Sensors Bundle
14	Transformer step-up

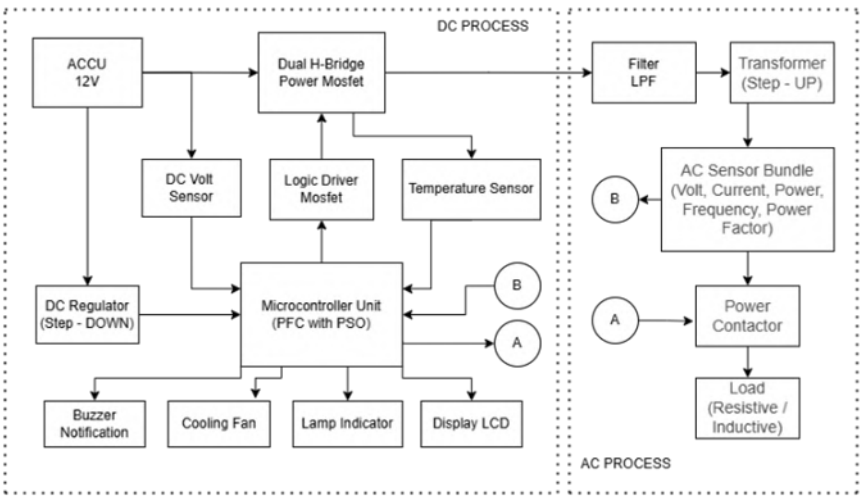


Figure 3. Inverter System Electrical Hardware Planning.

Figure 3 is the electrical hardware planning of the inverter system that will be made in this study. A 12VDC capacity battery is used as a DC voltage input for the inverter system which will be read by a DC voltage sensor to determine the voltage value generated by the battery and the sensor reading data will be sent to the ESP32 microcontroller for processing. ESP32 gets DC voltage input from the battery whose voltage value is reduced using a DC voltage regulator to 3.3VDC. ESP32 is used as data processing from the data sent by each sensor. In addition, ESP32 is used as a PWM signal generator for the MOSFET switching process assisted by an IR2110 driver. To find out the temperature value of the MOSFET, a temperature sensor is used to read and send the value to ESP32. The results of the inverter circuit switching process in the form of RMS voltage will be filtered using a Low Pass Filter (LPF) circuit with the aim of smoothing the signal results and can be a pure sinusoidal wave. After that, the voltage from the LPF circuit will be increased to AC 220V voltage using a step-up transformer. The result of the 220V AC voltage is used to supply voltage to resistive, inductive, and capacitive loads which will later be evaluated for its power factor value to remain stable according to the standard, which is> 0.85.

2.3. SPWM Signal Generation Planning

The generation of SPWM signals using ESP32 aims to generate PWM signals that can be used to control the inverter output voltage and frequency. Here are some steps for SPWM signal generation:

- Determine the frequency and period of the desired reference (sine) wave. This research uses a modulation frequency of 50Hz.

$$T_r = \frac{1}{f_r} = \frac{1}{50} = 0{,}02s \; or \; 20ms \tag{1}$$

- Determine the frequency and period of the carrier wave. This research uses a carrier frequency of 20kHz.

$$T_c = \frac{1}{f_c} = \frac{1}{20000} = 0{,}00005s \; or \; 0{,}05ms \; or \; 50\mu s \tag{2}$$

- Determines the number of pulses by comparing the period values of the reference signal and the carrier signal.

$$M_T = \frac{T_r}{T_c} = \frac{20ms}{0{,}05ms} = 400 \; squence \tag{3}$$

- Determining the sinusoidal value of each cycle, known modulation period ($\boldsymbol{T_m}$) in radians is equal to 2π.

$$M_T = \frac{T_m}{T_s} \rightarrow 400 = \frac{2\pi}{T_s}$$
$$T_s = \frac{2 \times 3{,}14}{400} = \frac{6{,}28}{400} = 0{,}0157\ rad/squence \quad (4)$$

- Determines the nth pulse width (duty cycle) (n = cycle value 0-399), for example the amplitude ($\boldsymbol{\alpha}$) is 100 and the figure shown in Figure 4.

$$V_n = \alpha \times \sin(0{,}0157 \times n)$$
$$V_0 = 100 \times \sin(0{,}0157 \times 0) = 0$$
$$V_1 = 100 \times \sin(0{,}0157 \times 1) = 1{,}57$$
$$V_2 = 100 \times \sin(0{,}0157 \times 2) = 3{,}14$$
$$V_3 = 100 \times \sin(0{,}0157 \times 3) = 4{,}71$$
$$V_4 = 100 \times \sin(0{,}0157 \times 4) = 6{,}28$$
$$V_5 = 100 \times \sin(0{,}0157 \times 5) = 7{,}84 \quad (5)$$
$$V_{100} = 100 \times \sin(0{,}0157 \times 100) = 99{,}99$$
$$V_{200} = 100 \times \sin(0{,}0157 \times 200) = 0$$
$$V_{250} = 100 \times \sin(0{,}0157 \times 250) = -6{,}02$$
$$V_{300} = 100 \times \sin(0{,}0157 \times 300) = -99{,}99$$
$$V_{399} = 100 \times \sin(0{,}0157 \times 399) = -1{,}88$$

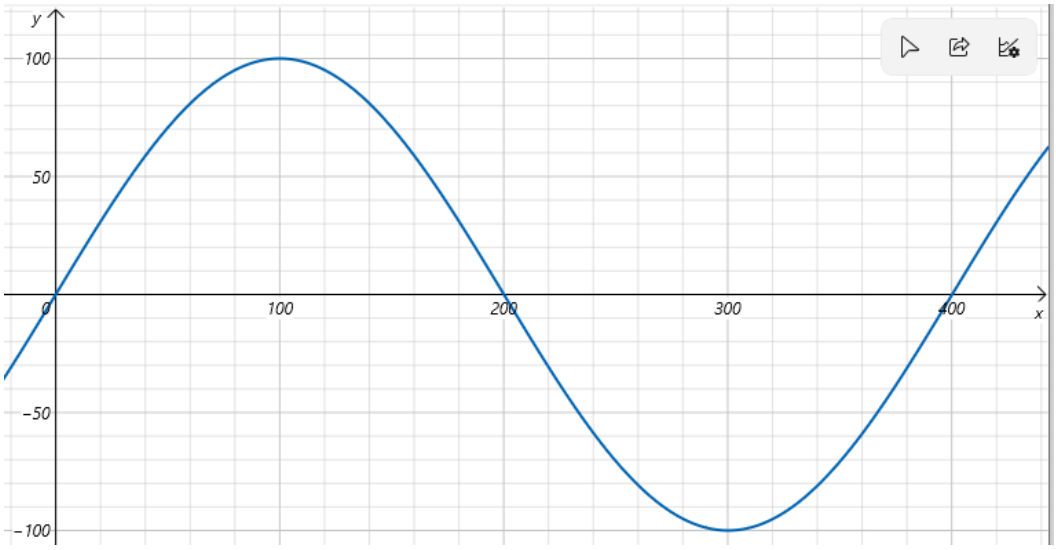


Figure 4. Amplitude Simulation Based on SPWM.

The results of the formula for finding the pulse width (duty cycle) of each cycle will be used in the ESP32 microcontroller programme to generate SPWM signals. In addition, the selection of the carrier frequency value was chosen because it is more optimal and with a frequency of 20kHz it is sufficient to achieve the purpose of planning the generation of SPWM signals in the inverter.

2.4. Power Factor Correction Planning

This plan aims to apply power factor correction to the inverter without using additional components such as capacitor banks, but through programming and PWM signal settings. The first step in using PFC is to measure the power factor value using the AC Sensor Bundle (PZEM004T sensor) integrated with the inverter system. The equation used to be implemented into the ESP32 programs.

$$pf = \frac{P}{\sqrt{P^2 - Q^2}} \tag{6}$$

$$ps = \cos^{-1}(pf) \tag{7}$$

The function uses the measured PZEM004T power factor value (pf) and returns as a phase shift in radians using the $\cos^{-1}$ function.

$$\text{If measured } pf = 0{,}8 \text{ then the phase shift value } ps = \cos^{-1}(0{,}8) = 0.6435 \tag{8}$$

The result of that phase shift (0.6435) is implemented in PWM signal modulation to regulate the inverter output signal.

$$P_{pwm} = 350 \text{ x } \sin(2\pi \times 50 \times \frac{1}{20000} + 0{,}6435) \tag{9}$$

2.5. Particle Swarm Optimisation Plannin

Particle Swarm Optimization is a method or algorithm used to optimize the phase difference between voltage (V) and current (I) at the inverter output. The purpose of optimizing the phase difference between voltage and current is to keep the power factor value close to 1 or equal to 1 when given different types of loads. This is very important so that the inverter can function more efficiently with various types of loads (resistive, inductive, and capacitive). The PSO flowchart starts the process by setting the parameters W (inertia weight), C_1 (cognitive constant), and C_2 (social constant) that govern the speed (V_i^t) and direction position of the particles (P_i^t). Once the parameters are set, the particles are randomly generated (U_1^t and U_2^t) to form an initial population which is then evaluated for its fitness value which reflects how well it optimizes the phase difference.

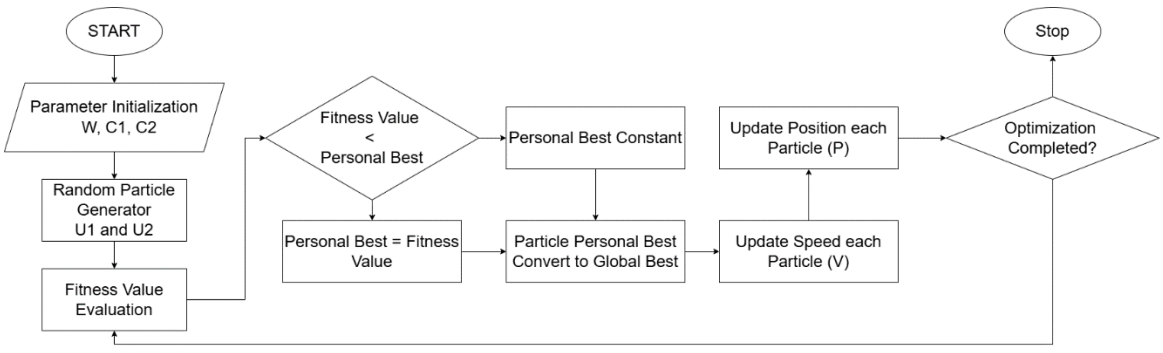


Figure 5. Flowchart Particle Swarm Optimization Method.

$$V_i^{t+1} = \mathrm{W}.V_i^t + C_1.U_1^t\left(P_{b_1}^t - P_i^t\right) + C_2.U_2^t(g_i^t - P_i^t) \quad (10)$$

$$P_i^{t+1} = P_i^t + V_i^{t+1} \quad (11)$$

After evaluating the fitness value, the next step is to compare the fitness value of each particle with $P_{b_1}^t$ (Personal Best). The comparison is done to find out the best position ever achieved by the particle. If the particle fitness value is better than $P_{b_1}^t$ then $P_{b_1}^t$ will be updated. The best $P_{b_1}^t$ of all particles will become the g_i^t (global best), which is the best particle position globally or overall. The velocity of each particle is updated based on the g_i^t and $P_{b_1}^t$ results respectively using a formula that considers inertia, cognitive (C_1), and social (C_2) factors. The particle speed (V_i^{t+1}) and particle positions (P_i^{t+1}) are also updated and this process repeats in desired iterations to find the optimal solution.

Table 2. Particle Swarm Optimization Initialization Variable

Variable	Value
W	0,5
C_1	1,5
C_2	1,5
t_{max}	100
i_{max}	30
U_1^t	$rand(0 \leq U_1^t \leq 1)$
U_2^t	$rand(0 \leq U_2^t \leq 1)$

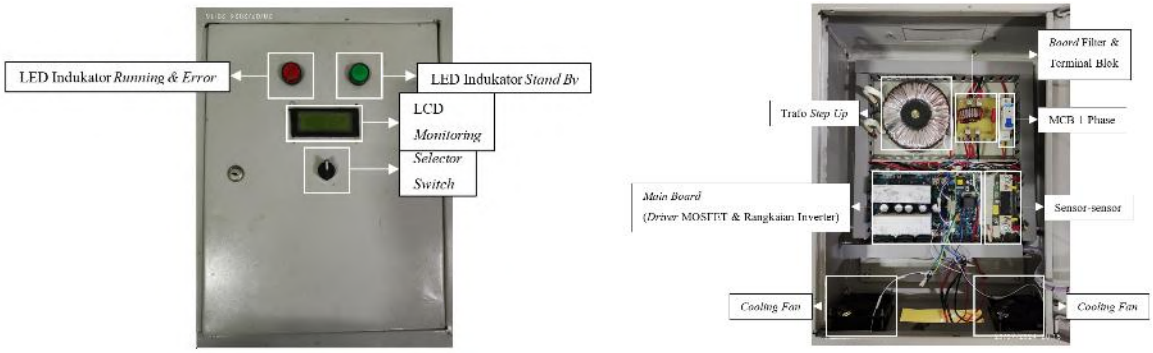
This iteration process continues until it reaches the desired optimization condition ($P_i^{t+1}\ eq\ Optimal$), which is an updated particle position or power factor (P_i^{t+1}) value close to 1 or equal to 1. The inverter can adapt to changes in load type and maintain high efficiency using the PSO method. In addition to optimizing the power factor, this method can also help reduce power losses and improve the operational stability of the electrical system in the inverter. This optimization is particularly useful in practical applications where inverters are used with different types of loads and ensure consistent performance. The workflow of the PSO method that will be used to support power factor improvement is described in the Figure 5.

3. Results

Based on the planning that has been done in the previous chapter and applied to this research. Then the results and discussion of power factor correction research on the inverter will be obtained. In chapter three will be described about the tests that have been carried out and will be discussed as detailed as possible. As well as comparisons will be made when research using the method and when research without using additional methods.

3.1. Inverter System Panel Box Design Results

The design of the inverter system panel box is an important stage in ensuring proper and safe installation of this research. Wiring the correct panel box will optimize the performance of the inverter system and ensure the safety of the user and the components used. The panel box functions as a provider of an organized place to arrange all electrical connections between the required components including power input, power output, and the required control system. The panel box used in this Final Project has a length x width x height of 40cm x 50cm x 20cm.



(a) (b)

Figure 6. (a) Front View of Box Panel, (b) Results of the Inside View of the Panel Box

Figure 6(a) shows some of the control components and indicators that are useful for monitoring and operating the inverter system. The top of the panel has red and green indicator LEDs. The red LED indicates the condition of the inverter system is working or can already produce 220V AC voltage and the indicator can function as an error indicator in the inverter system. The green LED indicates that the inverter system is in standby condition with the 12V DC voltage already connected. In the middle of the panel there is an I2C LCD which functions as monitoring data readings from sensors in real time. At the bottom of the LCD there is a selector switch that functions as a control to switch on and off the inverter system. If the selector switch is rotated clockwise, the inverter system will turn on or be in running condition.

Figurer 6(b) shows the inside view of the inverter system panel box which consists of various components such as a step up transformer to increase the output voltage to 220V, a board filter to filter sinusoidal wave noise and the bottom of the filter board there is a terminal block as an auxiliary terminal for 220V voltage output, as well as a 1 phase MCB section as overcurrent protection. The sensors section functions as data collection for monitoring and control of the inverter system. In addition, the main board consists of a MOSFET driver PCB and an inverter circuit PCB that converts DC current into AC. Finally, 2 cooling fans at the bottom aim to maintain the panel box temperature to remain optimal. The arrangement of the components in the panel box is designed for ease of maintenance and operational efficiency.

3.2. PWM Signal Generation Test Results

Figure 7(a) shows the measurement results of the PWM signal that will be used to control the IR2110 driver in controlling the MOSFET in the inverter system. This PWM signal has a frequency of 50Hz which shows how fast the PWM cycle is in one second. The right frequency is very important to ensure a fast and efficient response from the MOSFET. The resulting Duty Cycle is a constant 50% which means the signal is at its highest level for half a period in one cycle period. This Duty Cycle is generally used for symmetrical switching operations, ensuring that the MOSFET can be switched on and off with balanced switching. The ESP32 output pin under test is pin 27 which is connected to the first 1LIN pin of IR2110.

The resulting $\boldsymbol{V_{pp}}$voltage is 3.52V, indicating the voltage difference between the highest and lowest levels of the PWM signal which must match the input specifications of the IR2110 driver. The average voltage ($\boldsymbol{V_{avg}}$) shows a result of 1.63V which means it gives an indication of the DC effect of the PWM signal which can affect the switching characteristics of the MOSFET. The RMS voltage ($\boldsymbol{V_{rms}}$) shows a value of 2.30V which is important for determining the effective energy delivered by the PWM signal to the load. The maximum voltage ($\boldsymbol{V_{max}}$) of the signal is 3.39V and the minimum voltage ($\boldsymbol{V_{min}}$) is 0.13V. This is important to ensure that the PWM signal reaches the logic levels required to properly switch the MOSFETs on and off.

(a) (b)

Figure 7. (a) PWM Pin 27 Output Testing Results, (b) PWM Pin 26 Output Testing Results

(a) (b)

Figure 8. (a) PWM Output Testing Results Pin 18, (b) PWM Pin 19 Output Testing Results

Figure 7(b) shows the results of testing the PWM signal output pin 26 of the ESP32 connected to pin 1HIN of the first IR2110 driver. This signal has a frequency of 50Hz and a duty cycle of 50% with a constant or invariable value. This aims to ensure symmetrical switching of the MOSFETs for stable and efficient operation. The peak-to-peak voltage ($\boldsymbol{V_{pp}}$) shows a result of 3.56V, an average voltage ($\boldsymbol{V_{avg}}$) of 1.63V, and an RMS voltage ($\boldsymbol{V_{rms}}$) of 2.37V. In addition, the maximum voltage ($\boldsymbol{V_{max}}$) and minimum voltage ($\boldsymbol{V_{min}}$) yielded values of 3.44V and 0.12V, respectively. This ensures that the signal reaches the logic level required to switch the MOSFET on and off.

3.3. Step Up Transformer Testing Results

Figure 9 shows the results of testing the output of the step up transformer after the filtration process using LPF. Based on Figure 4.29, the peak-to-peak voltage ($\boldsymbol{V_{pp}}$) can reach 617.00V with a maximum voltage of 307.00V and a minimum voltage of -310.00V. The resulting signal frequency is still fixed at 50Hz, but the duty cycle results sometimes drop at 48% and sometimes back at 50%. The average voltage ($\boldsymbol{V_{avg}}$) generated is around -3.00V to -4.00V. In addition, the resulting RMS voltage ($\boldsymbol{V_{rms}}$) of 220.40V gives an indication of an effective value and is in line with expectations for residential electrical loads.

Figure 9. Step Up Transformer Testing Results.

The results of this test show that the toroidal type step up transformer has successfully increased the output voltage after filtration. It also shows that the AC voltage of the sinusoidal wave is in accordance with the needs of residential electrical loads. In addition, this measurement shows that the toroidal type step up transformer works efficiently, producing a stable and symmetrical output voltage close to 0V which is important for maintaining signal quality and ensuring reliable operation of the electrical load to be connected to the inverter system.

4. Discussion

4.1. Test Results of Inverter System Without Method

Tests were carried out using resisitive and inductive loads. The electrical loads used are 40W incandescent lamps, 100W incandescent lamps, 40W fans, and 200W blenders. Tests are carried out alternately to determine changes in the power factor value of each load tested. The following are the results of the tests that have been carried out. The results of testing the inverter system without the method show stable results according to the type of load used. including resistive, inductive, and mixed resistive-inductive loads. The resistive loads, specifically 40W and 100W lamps, maintain a stable power factor (PF) of 1.00, indicating that these loads exhibit purely active power consumption with no reactive component.

Table 3. Inverter System Testing Results Without PSO Method

NO.	TYPE LOADS	OUTPUT PARAMETERS				
		V (V)	I (A)	P (W)	F (Hz)	PF
1	Res. 40W	215,30	0,18	37,68	50,00	1,00
2		215,29	0,18	38,75	50,00	1,00
3		214,70	0,17	36,50	50,00	1,00
4		215,10	0,18	38,72	50,00	1,00
5		215,10	0,18	38,73	50,00	1,00
6	Res. 100W	186,10	0,40	74,07	50,00	1,00
7		185,00	0,38	70,30	50,00	1,00
8		186,10	0,40	74,44	50,00	1,00
9		186,10	0,40	74,44	50,00	1,00
10		186,30	0,39	72,66	50,00	1,00
11	Induc. 40W	214,60	0,18	37,56	50,00	0,55
12		205,90	0,18	36,44	50,00	0,55
13		211,90	0,18	37,93	50,00	0,55
14		212,20	0,18	37,77	50,00	0,55
15		210,10	0,18	36,77	50,00	0,55
16	Induc. 200W	129,70	0,72	93,38	50,00	0,99
17		129,00	0,74	94,94	50,00	0,93
18		128,70	0,73	93,69	50,00	0,99
19		128,50	0,74	94,45	50,00	0,98
20		129,00	0,74	94,82	50,00	0,98
21	Res. & Indc.	183,90	0,29	53,33	50,00	0,90
22		183,90	0,29	53,33	50,00	0,90
23		199,90	0,29	57,97	50,00	0,90
24		200,10	0,29	58,03	50,00	0,89
25		200,03	0,29	58,01	50,00	0,90

The recorded voltage for these loads ranges from 185V to 215V, with corresponding current values between 0.17A and 0.40A, leading to power outputs between 36.50W and 74.44W. This expected behavior confirms that resistive loads do not introduce phase shifts between voltage and current, resulting in maximum power efficiency. However, the inductive loads, such as 40W fans and 200W blenders, exhibit a significant drop in power factor due to the presence of reactive power. The 40W fan load shows a power factor of 0.55, implying that nearly 45% of the apparent power is reactive, causing inefficiencies. The power readings for this load range from 36.44W to 37.77W, with a steady current of 0.18A, demonstrating that inductive components cause phase delays between voltage and current. For 200W inductive loads (blenders), the power factor improves to 0.90, indicating partial compensation for reactive power, likely due to the nature of the load or internal correction mechanisms. The power consumption in this category fluctuates between 93.38W and 94.94W, with current values of 0.72A to 0.74A, signifying that while inductive effects still exist, they are less pronounced compared to smaller inductive loads. When examining resistive and inductive loads combined, the power factor falls between 0.89 and 0.90, showing a balance between active and reactive power. The total power consumption in this scenario ranges from 53.33W to 58.01W, with voltage values between 183.90V and 200.03V, while the current stabilizes around 0.29A.

4.2. Inverter System Testing Results With Methods

This electrical load testing aims to optimise the performance of the inverter using the Particle Swarm Optimisation (PSO) method. Various types of loads, both resistive and inductive, are tested individually and in combination to analyse their effect on the power value and power factor. The use of PSO is expected to find the best inverter configuration capable of producing optimal power and improving power factor, especially on inductive loads. Tests were conducted using a 12VDC battery as an energy source.

Based on Table 4 the test results of the power factor value on a 100W incandescent lamp load get a value of 1.00 as well as an incandescent lamp with a capacity of 40W. This is a very efficient value because in resistive loads there is no reactive power component so that the voltage and current waves are in phase. The resistive loads, represented by 40W and 100W lamps, continue to exhibit an optimal power factor (PF) of 1.00 or close to 0.99, confirming that these loads remain purely active with minimal or no reactive power losses. The recorded voltage levels range from 198V to 215V for 40W lamps and 169V for 100W lamps, with current values between 0.17A and 0.40A, resulting in power values from 34.67W to 67.38W. This behavior is consistent with expectations for resistive loads, where the voltage and current remain in phase, ensuring maximum power conversion efficiency. The impact of the PSO method becomes particularly evident in inductive loads, such as 40W fans and 200W blenders, where the power factor has notably improved compared to results from the non-PSO method in Table 3. The 40W fan load, which previously had a power factor of 0.55, now exhibits an increased power factor ranging from 0.57 to 0.60, demonstrating a reduction in the phase shift between voltage and current. The corresponding power consumption varies between 34.20W and 36.54W, with a steady current of 0.17A, suggesting that PSO optimizes the inverter's response to inductive characteristics, mitigating some reactive power losses. A more pronounced improvement is observed in 200W inductive loads (blenders), where the power factor remains consistently high, reaching 0.98, compared to 0.90 in the previous test without PSO. The power output fluctuates between 95.63W and 99.33W, with current values around 0.71A to 0.73A, indicating that PSO significantly enhances power conversion efficiency for larger inductive loads by optimizing control parameters to minimize energy losses. When analyzing mixed resistive and inductive loads, the power factor has also seen a notable increase, reaching values between 0.91 and 0.99, compared to the 0.89 - 0.90 range in the non-PSO test. The total power consumption varies from 55.85W to 60.05W, with voltage levels between 201V and 203V, while the current stabilizes around 0.28A to 0.30A.

Table 4. Inverter System Testing Results Using the PSO Method

NO.	TYPE LOADS	OUTPUT PARAMETERS				
		V (V)	I (A)	P (W)	F (Hz)	PF
1	Res. 40W	215,30	0,17	36,17	50,00	0,99
2		206,30	0,17	35,28	50,00	0,99
3		215,30	0,18	37,68	50,00	1,00
4		198,10	0,18	34,67	50,00	1,00
5		215,30	0,17	36,39	50,00	1,00
6	Res. 100W	169,30	0,40	67,38	50,00	0,99
7		169,10	0,40	67,30	50,00	1,00
8		169,10	0,39	65,44	50,00	1,00
9		169,00	0,39	65,07	50,00	1,00
10		169,00	0,39	66,25	50,00	1,00
11	Induc. 40W	207,30	0,17	34,20	50,00	0,58
12		209,50	0,17	35,20	50,00	0,60
13		207,70	0,17	34,48	50,00	0,57
14		217,70	0,17	36,14	50,00	0,59
15		217,50	0,17	36,54	50,00	0,60
16	Induc. 200W	138,50	0,71	98,06	50,00	0,98
17		135,70	0,73	99,33	50,00	0,99
18		129,90	0,73	95,09	50,00	0,99
19		131,00	0,73	95,63	50,00	0,99
20		135,00	0,73	98,55	50,00	0,99
21	Res. & Indc.	203,10	0,28	55,85	50,00	0,91
22		201,10	0,29	58,92	50,00	0,90
23		200,80	0,27	54,42	50,00	0,91
24		202,20	0,30	60,05	50,00	0,91
25		203,30	0,28	56,31	50,00	0,99

4.3. Comparison Power Factor Correction Result

Specifically, this research wants to know the extent to which the PSO method can improve inverter efficiency under various load conditions. Through the analysis of the data obtained, it is expected to gain a deeper understanding of the factors that affect inverter performance. The results of this research are expected to contribute to the development of a more efficient and reliable inverter system, and become a reference for further research in the field of power system optimisation.

The comparison between PF Without Methods and PF With Methods reveals that, in most cases, the application of the method leads to an increase in the power factor. For resistive loads, the power factor remains unchanged at 1.00, indicating that resistive loads naturally exhibit unity power factor with or without additional optimization. However, the impact of the applied method becomes evident in inductive loads, where the power factor improves noticeably.

Table 5. Comparison Power Factor Results with and without the PSO Method

NO.	TYPE LOADS	PF Without Methods	PF With Methods	Difference Value Result	Total Difference	Average
1	Res. 40W	1,00	0,99	-0,01	0,36	0,0144
2		1,00	0,99	-0,01		
3		1,00	1,00	0		
4		1,00	1,00	0		
5		1,00	1,00	0		
6	Res. 100W	1,00	0,99	-0,01		
7		1,00	1,00	0		
8		1,00	1,00	0		
9		1,00	1,00	0		
10		1,00	1,00	0		
11	Induc. 40W	0,55	0,58	0,03		
12		0,55	0,60	0,05		
13		0,55	0,57	0,02		
14		0,55	0,59	0,04		
15		0,55	0,60	0,05		
16	Induc. 100W	0,99	0,98	-0,01		
17		0,93	0,99	0,06		
18		0,99	0,99	0		
19		0,98	0,99	0,01		
20		0,98	0,99	0,01		
21	Res. & Indc.	0,90	0,91	0,01		
22		0,90	0,90	0		
23		0,90	0,91	0,01		
24		0,89	0,91	0,02		
25		0,90	0,99	0,09		

The Table 5 of Comparison Power Factor Results with and without the PSO Method provides an in-depth analysis of how Particle Swarm Optimization (PSO) enhances power factor (PF) across different types of electrical loads, including resistive, inductive, and mixed resistive-inductive loads. The results indicate that resistive loads consistently maintain a PF of 1.00, with minimal variations due to PSO. However, the greatest impact of PSO is observed in inductive and mixed loads, where noticeable improvements in power factor are recorded. For the 40W inductive load, the power factor increases from 0.55 to values between 0.57 and 0.60, with improvements ranging from 0.02 to 0.05, illustrating PSO's effectiveness in mitigating phase shifts caused by inductive elements. Similarly, in the case of 100W inductive loads, the power factor remains stable or improves slightly, reaching up to 0.99, indicating that PSO helps maintain high energy efficiency by optimizing reactive power management. The most substantial improvements occur in mixed resistive-inductive loads, where the power factor rises from 0.89 to 0.99, with some instances showing a 0.09 increase, highlighting PSO's role in optimizing inverter performance and minimizing energy losses. Overall, the total improvement across all tested conditions amounts to 0.36, with an average increase of 0.0144 per measurement, demonstrating PSO's consistent contribution to power quality enhancement.

5. Conclusions

This research successfully demonstrates the development and testing of an inverter design with and without the implementation of the Particle Swarm Optimization (PSO) method. The inverter was tested using various types of electrical loads, including resistive loads (40W and 100W lamps),

inductive loads (40W fan and 200W blenders), and a combination of resistive and inductive loads. The results indicate that resistive loads inherently maintain a near-unity power factor (PF ≈ 1.00) with minimal variation, as they do not introduce reactive power. However, for inductive loads, the power factor significantly improves with the implementation of PSO, demonstrating that the optimization technique effectively compensates for reactive power and minimizes phase shifts between voltage and current. The 40W inductive fan, which initially exhibited a PF of 0.55 without PSO, improved to values between 0.57 and 0.60 with PSO, while the 200W inductive blender load saw its power factor increase up to 0.98. Furthermore, in mixed resistive-inductive loads, the power factor increased from 0.89 to as high as 0.99, highlighting PSO's capability in optimizing overall system performance. The total recorded power factor improvement across all tested scenarios amounted to 0.36, with an average increase of 0.0144 per case, reinforcing the benefits of PSO in real-world inverter applications. From these findings, it is evident that the PSO method plays a crucial role in improving power quality, reducing reactive power losses, and enhancing the efficiency of inverter-based systems, particularly in environments where inductive loads dominate.

References

1. Sugito, Analisis Pengaruh Beban Terhadap Efisiensi Daya Pada Modified Sine Wave Inverter Dan Pure Sine Wave Inverter. Jakarta, 2022.
2. Mohammad Luqman, Achmad Komarudin, And Sidik Nurcahyo, "Pembangkit Sinusoida Pulse Width Modulation Berbasis Arduino Untuk Inverter," Jurnal Teknik Ilmu Dan Aplikasi, Vol. 3, Pp. 42–46, Oct. 2022.
3. Lalu Riza Aliyan, Rini Nur Hasanah, And M. Aziz Muslime, "Desain Inverter Tiga Fasa Dengan Minimumtotal Harmonic Distortion Menggunakan Metode Spwm," Jurnal Eeccis, Vol. 8, No. 1, Pp. 79–84, Jun. 2014.
4. Ikhwan Romadhoni, Awan Uji Krismanto, And Abraham Lomi, "Rancang Bangun Kendali Inverter Berbasis Arduino Dengan Metode Spwm," Magnetika: Jurnal Mahasiswa Teknik Elektro, Vol. 8, No. Vol. 8 No. 1 (2024): Magnetika: Jurnal Mahasiswa Teknik Elektro, Pp. 433–440, May 2024.
5. Khairul Azmi, Ira Devi Sara, And Syahrizal, "Desain Dan Analisis Inverter Satu Fasa Dengan Menggunakan Metode Spwm Berbasis Arduino," Kitektro: Jurnal Online Teknik Elektro, Vol. 2, Pp. 36–44, 2017.
6. S. Nurhadi, M. Saputra, And A. Dasa Nofvowan, "Desain Dan Uji Performa Trafo Toroid Satu Fasa Pada Aplikasi Inverter Berbasis Egs002," Jurnal Teknik Ilmu Dan Aplikasi, Vol. 3, No. 2, Pp. 46–53, Oct. 2022, [Online]. Available: Http://Jurnal.Polinema.Ac.Id/Index.Php/Jtia/Article/View/1663
7. R. A. Amrullah, Herwandi, And Agus Pracoyo, "Perancangan Dan Pembuatan Inverter Pure Sine Wave 150watt Dengan Feedback Ac 220/50hz Berbasis Mikrokontroller Arduino," Jurnal Elkolind, Vol. 8, No. 2, Pp. 96–100, Jul. 2021.
8. S. Dinasti, M. Luqman, And A. Pracoyo, "Pembangkit Sinyal Spwm Berbasis Arduino Uno," Jurnal Elkolind, Vol. 9, No. 1, Pp. 70–75, May 2022.
9. R. D. Rachwanto, S. Saidah, And A. Amirullah, "Implementasi Inverter Berbasis Square Wave Dan Sinusoidal Pwm Menggunakan Arduino Uno," Rekayasa, Vol. 15, No. 2, Pp. 182–191, Aug. 2022, Doi: 10.21107/Rekayasa.V15i2.13454.
10. L. Santoso, A. M. N. Imron, And B. S. Kaloko, "Perancangan Inverter Satu Fasa Berbasis Arduino Menggunakan Metode Spwm," Techné : Jurnal Ilmiah Elektroteknika, Vol. 22, No. 1, Pp. 85–96, Apr. 2023, Doi: 10.31358/Techne.V22i1.351.
11. M. A. Syururi, B. S. Kaloko, And W. Cahyadi, "Rancang Bangun Inverter 600 Watt Dengan Metode Sinusoidal Pulse Width Modulation," Jurnal Teknik Elektro Dan Komputer, Vol. 11, No. 3, Pp. 147–154, Dec. 2022.
12. A. J. Maabuat, Sherwin R.U.A., Sompie, And M. Rumbayan, "Perancangan Proteksi Inverter Berbasis Arduino Uno," Jurnal Teknik Elektro Dan Komputer, Vol. 19, No. 1, Pp. 39–48, Jan. 2020.
13. Y. Esye And S. Lesmana, "Analisa Perbaikan Faktor Daya Sistem Kelistrikan," Jurnal Sains & Teknologi, Vol. Xi, Pp. 103–113, Mar. 2021.

14. F. C. Kurniawan, "Perbaikan Faktor Daya Listrik Secara Otomatis Menggunakan Mikrokontroler Arduino Mega 2560 Dengan Tampilan Hmi Scada ," Tugas Akhir, Universitas Diponegoro, Semarang, 2021.
15. M. F. Roslan, A. Q. Al-Shetwi, M. A. Hannan, P. J. Ker, And A. W. M. Zuhdi, "Particle Swarm Optimization Algorithm-Based Pi Inverter Controller For A Grid-Connected Pv System," Plos One, Vol. 15, No. 12, P. E0243581, Dec. 2020, Doi: 10.1371/Journal.Pone.0243581.
16. H. Mubarok And B. A. Whiancaka, "Optimasi Sistem Turbin Angin Menggunakan Maximum Power Point Tracking (Mppt) Dengan Metode Particle Swarm Optimization (Pso)," Techné : Jurnal Ilmiah Elektroteknika, Vol. 19, No. 01, Pp. 1–10, Apr. 2020, Doi: 10.31358/Techne.V19i01.226.
17. W. Safaroz, "Rancang Bangun Dan Proteksi Inverter Pure Sine Wave Spwm 500 Watt Berbasis Mikrokontroler Menggunakan Fuzzy Logic," Jurnal Informatika Dan Teknik Elektro Terapan, Vol. 11, No. 3, Jul. 2023, Doi: 10.23960/Jitet.V11i3.3304.

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Article

A Simple Modeling of MPPT-based ANN for Photovoltaic System

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Abstract: This research describes a simple modeling technique for Maximum Power Point Tracking based on Artificial Neural Network (MPPT-based ANN) for photovoltaic (PV) systems. The proposed ANN model utilizes a feed-forward backpropagation architecture. The PV system was developed and tested in a simulation environment under uniform irradiation levels of 1000 W/m², 800 W/m², and 600 W/m², and rapidly varying irradiation changes. The simulation results demonstrate that the MPPT-based ANN accurately tracks the MPP, achieving stable power outputs of 98.36 W, 79 W, and 57.45 W, respectively. Although the system experiences initial transient oscillations during the tracking phase, it stabilizes within 80 milliseconds, showcasing rapid convergence and high steady-state accuracy. Under dynamic conditions, the MPPT-based ANN adapts effectively to fast-changing irradiation, restarting the algorithm to track and maintain the system at the updated MPP accurately. These results highlight the reliability, adaptability, and suitability of the MPPT-based ANN for real-time applications in dynamic environments. Nonetheless, further improvements to the ANN model are suggested to minimize transient oscillations and enhance overall performance.

Keywords: MPPT-based ANN, PV System, uniform irradiation.

1. Introduction

The rapid growth of photovoltaic (PV) system installations worldwide underscores their critical role in addressing energy demands sustainably. PV modules are connected in series-parallel arrangements to create PV arrays, convert sunlight into electrical energy through the photovoltaic effect. With the global push to reduce carbon emissions and adopt clean energy solutions, PV systems have become a vital component of renewable energy strategies. Their numerous advantages, including environmental friendliness, minimal maintenance requirements, and scalability, make them a preferred choice across residential, commercial, and industrial sectors. However, environmental factors such as sun irradiance, temperature, and shading conditions all have a substantial impact on PV system efficiency. These variables can lead to suboptimal power output, necessitating innovative solutions to optimize performance[1] [2] [3].

Maximizing energy extraction from PV systems requires operating them at their Maximum Power Point (MPP), the specific point where power output is at its highest. However, the MPP is dynamic and fluctuates with environmental conditions, creating challenges in maintaining optimal performance. To address this, Maximum Power Point Tracking (MPPT) algorithms are vital for ensuring PV systems consistently achieve peak power output, even under variable conditions. Over

time, numerous MPPT techniques have been developed, with traditional methods like Perturb and Observe (P&O) and Incremental Conductance (IncCond) gaining popularity due to their simplicity and reliability. Despite their widespread use, these methods often face challenges such as slower response times, steady-state oscillations, and decreased accuracy in rapidly changing environmental scenarios [4] [5] [6].

To address the shortcomings of traditional MPPT methods, advanced approaches leveraging artificial intelligence have gained prominence. Among these, Maximum Power Point Tracking based on Artificial Neural Networks (MPPT-based ANN) has emerged as a promising solution. ANN-based MPPT algorithms utilize machine learning techniques to model and predict the MPP with high accuracy. By learning from historical data and patterns, these algorithms can adapt swiftly to changes in environmental conditions, significantly enhancing the speed and precision of MPP tracking. Unlike conventional methods, ANN-based approaches are capable of minimizing steady-state oscillations and improving tracking performance in dynamic operating conditions, making them well-suited for real-time applications [7].

This paper focuses on the implementation and evaluation of an MPPT-based ANN algorithm for PV systems. The study aims to highlight the advantages of ANN-based algorithms in terms of efficiency, reliability, and adaptability. The results demonstrate that ANN-based MPPT algorithms not only achieve faster convergence to the MPP but also maintain steady-state accuracy under both uniform and rapidly changing environmental conditions. These findings underscore the potential of ANN-based MPPT as a robust and efficient solution for optimizing PV system performance. With the increasing complexity of environmental challenges, the integration of intelligent algorithms such as MPPT-based ANN represents a significant step toward enhancing the sustainability and reliability of solar energy generation.

2. Materials and Methods

This section discussed research related to the materials and methods to develop the PV system with the MPPT technique, such as PV module characteristic, Buck-Boost Converter, artificial neural network architecture, and MPPT-based ANN algorithm.

2.1 PV Module Characteristic

The equivalent circuit of a PV cell comprises a parallel current source combined with diodes and resistors connected to its output terminals [8]. PV cells are placed in series-parallel configuration to create a PV module, which generates a significant amount of electrical power. The power output of a PV module is heavily dependent on solar irradiation levels, with increased irradiation leading to higher power production. PV modules display non-linear behavior, commonly depicted through I-V and P-V curves. Any variation in irradiation conditions causes the PV module to function at a distinct Maximum Power Point (MPP). In this research, a 100 Wp PV module is employed to test the proposed algorithm and its P-V characteristics depicted in Figure 1.

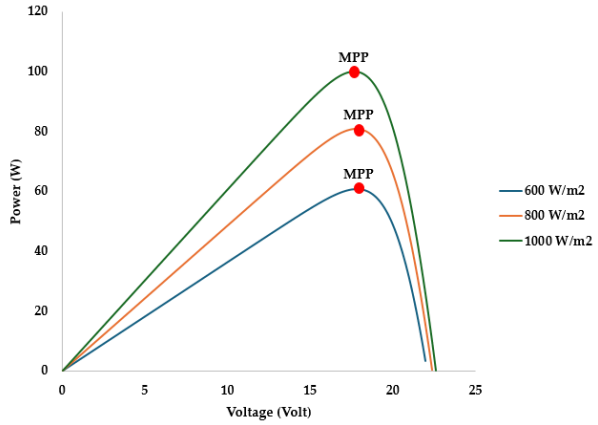

Figure 1. The P-V Characteristic of the PV Module

2.2 Buck-Boost Converter

A Buck-Boost Converter is used to apply the MPPT method between the PV module and the load. The PV module can operate within its Maximum Power Point (MPP) range by regulating the load impedance through changes in the duty cycle of the switching converter. Figure 2 displays the Buck-Boost Converter's circuit diagram, and Table 1 lists the values that were used in this investigation.

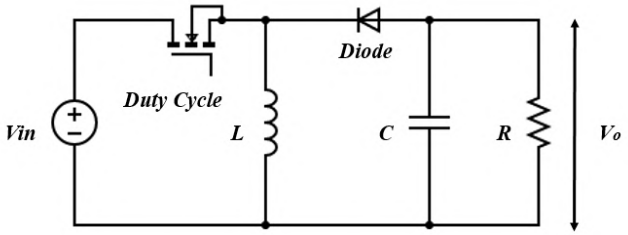

Figure 2. The Topology of the Buck-Boost Converter

Table 1. The parameters of the Buck-Boost Converter

No	Parameter	Variable	Value
1	Switching Frequency	f	40 kHz
2	Inductor	L	200 uH
3	Capacitor	C	560 µF
4	Load Resistor	R	40 Ω
5	Input Voltage	V_{in}	10-25 V
6	Output Voltage	V_0	5-225 V

2.3 Artificial Neural Network Architecture

The ANN is trained using 81 datasets that includes the duty cycle of the Buck-Boost Converter (D) as the output and the short-circuit current of the PV module (I_{sc}) as the input using MATLAB's NNTOOL program. In this study, several ANN architectures were created with different ANN setting as shown in Table 2. After training process, the best ANN architecture for this study has five neurons in the hidden layer with a tansig function in the output layer and a logsig activation function in the hidden layer, as shown in Figure 3. The best ANN architecture has a regression value of 0.99, which means that the model successfully predicts the target output perfectly, where all predicted values are identical to the target values as shown in the regression plot in Figure 4.

Table 2. The comparison of the ANN Architectures with Different ANN Setting

Architecture	Hidden Layer		Output Layer		MSE
	The Number of Neurons	Function	The Number of Neurons	Function	
1	3	logsig	1	tansig	3.05
2	5	logsig	1	tansig	0.94
3	7	logsig	1	tansig	5.08
4	10	logsig	1	tansig	9.02

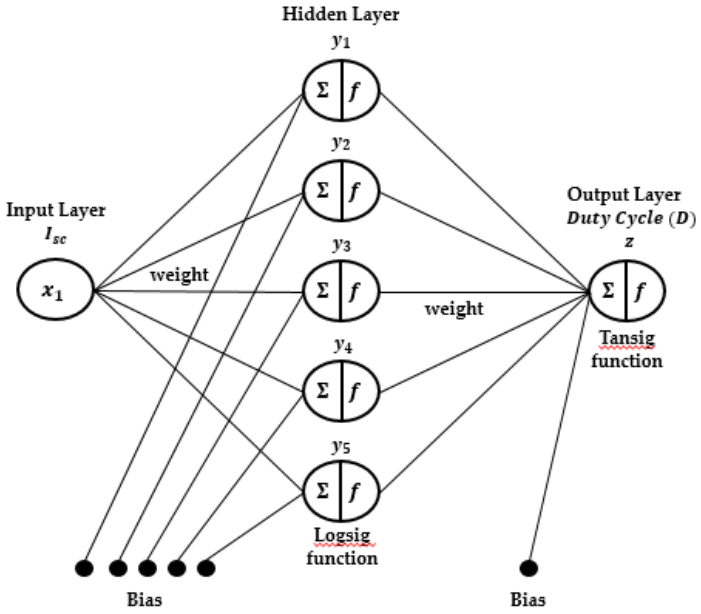

Figure 3. ANN Architecture

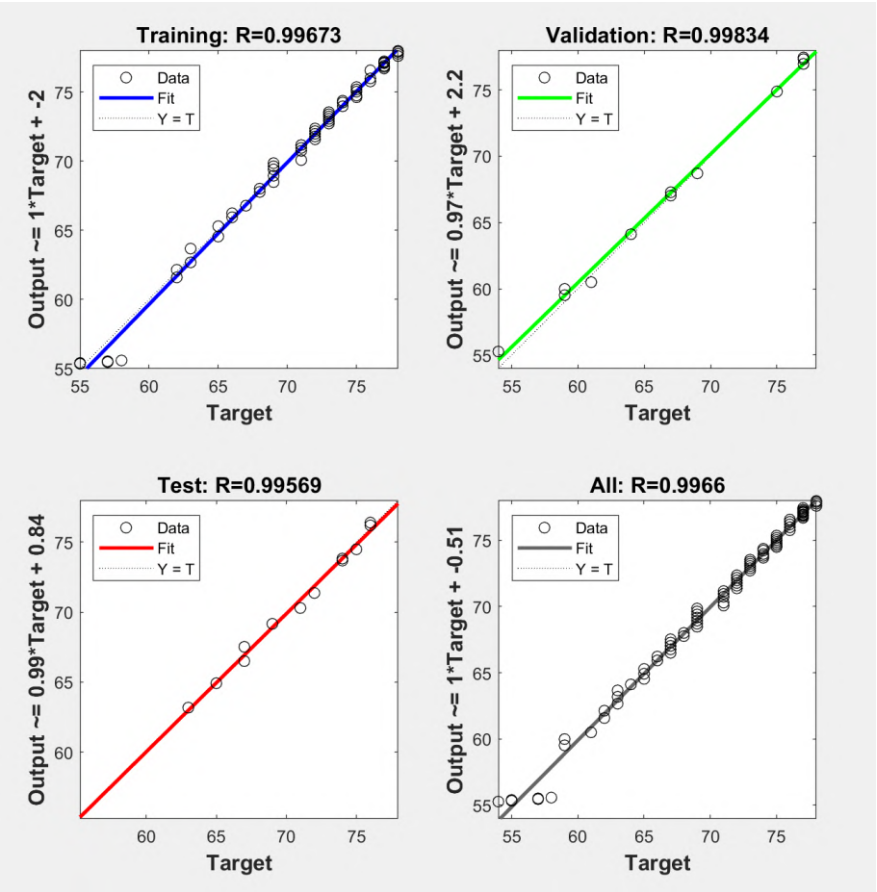

Figure 4. Regression Plot of The Best ANN Architecture

As illustrated in Figure 3, the ANN architecture can be represented as a mathematical model. Within the input layer, the short-circuit current is transformed into a standardized ANN value through a process known as input normalization. The corresponding mathematical model is provided in Equation (1).

$$x_1 = \frac{(I_{sc} - I_{sc,min}) * 2}{(I_{sc,max} - I_{sc,min})} - 1 \quad (1)$$

Here, x_1 represents the normalized input, I_{sc} denotes the short-circuit current, $I_{sc,min}$ is the minimum short-circuit current, and $I_{sc,max}$ is the maximum short-circuit current, both determined from the training data. The value of x_1 is then utilized in subsequent calculations within the hidden layer. The mathematical model is provided in Equation (2).

$$y_n = \frac{1}{(1 + e^{((x_1 * w_{in}) + b_{in})})} \quad (2)$$

In this context, i denotes the layer index, n represents the number of neurons, y_n is the output from each neuron, w signifies the weight, and b refers to the bias in the ANN. The weight and bias values are optimized during the training process conducted using MATLAB software. The output y_n is subsequently applied in the calculations for the output layer. The mathematical model is expressed in Equation (3).

$$z = \frac{2}{(1 + e^{(-2 * \sum_{n=1}^{5}((y_n * w_{in}) + b_{in}))})} - 1 \quad (3)$$

Where z is the result of the output layer. So, the duty cycle as an output can be calculated with Equation (4).

$$D = \frac{(z + 1)(D_{max} - D_{min})}{2} + D_{min} \quad (4)$$

Where D_{max} is the maximum duty cycle and D_{min} is the minimum duty cycle. The value of D_{max} and D_{min} are based on the training data.

2.4 MPPT-based ANN Architecture

The flowchart illustrating the proposed MPPT algorithm utilizing ANN is presented in Figure 5. The process starts with system initialization, during which key parameters, including voltage, current, and ANN settings such as weights and biases, are established. The process starts by measuring the short circuit current (I_{sc}) of the PV system, which serves as an input to the ANN model. Using the measured I_{sc} and predefined equations (Equations (1), (2), (3), and (4)), the ANN model estimates the duty cycle required to operate the PV system at the maximum power point (MPP) area. Next, the system measures the PV voltage (V_{pv}) and current (I_{pv}) at the current operating point. The power output (P_{pv}) at the MPP area is then calculated using $P_{pv} = V_{pv} \times I_{pv}$. The system continuously monitors irradiation levels, if a change in irradiation is detected, the process loops back to measure I_{sc} and re-estimate the duty cycle using the ANN model. If no change is detected, the system maintains the current operating conditions, completing the MPPT process. This iterative process ensures efficient tracking of the MPP under varying irradiation conditions.

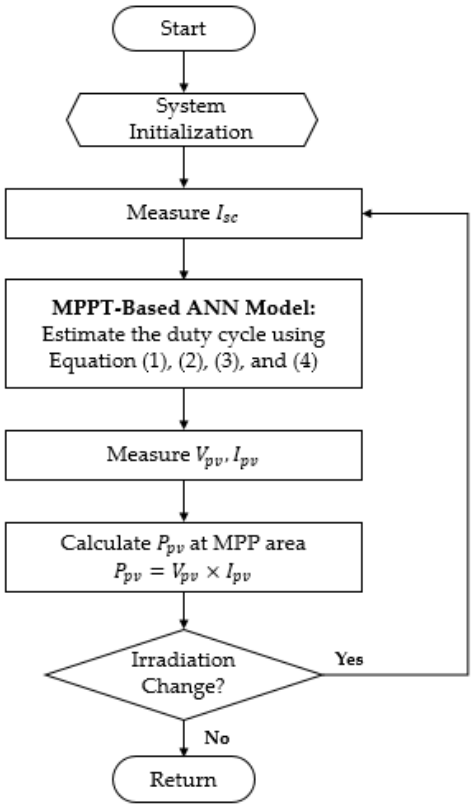

Figure 5. The Flowchart of MPPT-Based ANN

3. Results and Discussion

PSIM software simulations are used to validate the performance of the suggested MPPT-based ANN. As shown in Figure 6, the simulated PV system consists of a PV module connected to a resistive load and a Buck-Boost Converter, utilizing the MPPT-based ANN controller. The effectiveness and dependability of the MPPT-based ANN algorithm are evaluated by testing the system under various uniform irradiation levels and dynamic irradiation fluctuations.

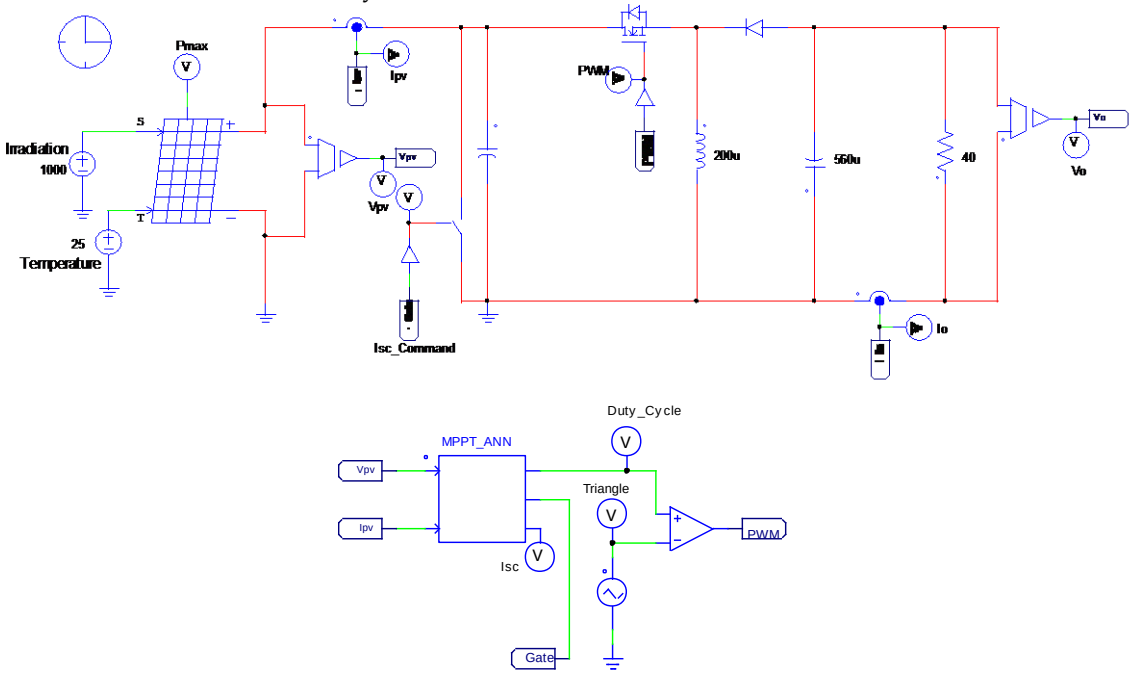

Figure 6. The PV System in PSIM Software

3.1 Under Uniform Irradiation

The PV system is evaluated under various uniform irradiation conditions, including 1000 W/m², 800 W/m², and 600 W/m². Each irradiation situation has a unique maximum power point (MPP) region. The MPPT-based ANN algorithm was validated by comparing it to training data. In case 1, the MPPT-based ANN tested under uniform irradiation 1000W/m². The simulation result shown in Figure 7. The graph illustrates the performance of MPPT-based ANN algorithm in achieving and maintaining the Maximum Power Point (MPP). The green line represents the real MPP, while the red line shows the MPPT-based ANN algorithm result. Initially, the MPPT-based ANN exhibits oscillations during the tracking phase (0-90 milliseconds) as it adjusts and converges to the MPP at 98,36 W. These oscillations diminish over time, with the system stabilizing at approximately 96 milliseconds, reflecting its ability to achieve steady-state power output efficiently. The ANN-based MPPT demonstrates rapid response times and a high degree of accuracy, maintaining the MPP area once stability is reached.

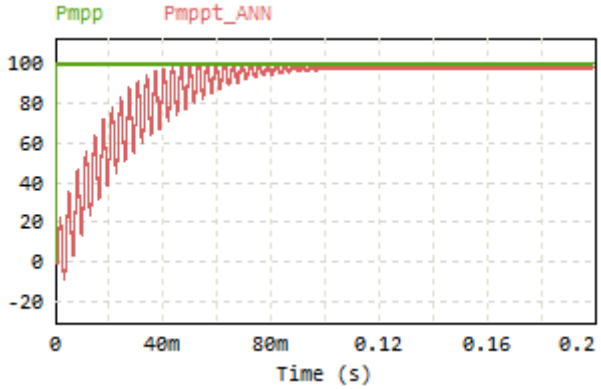

Figure 7. The Result of the Simulation for Case 1

In case 2, the MPPT-based ANN tested under uniform irradiation 800W/m². The simulation's outcome is displayed in Figure 8. Initially, during the tracking phase (0 to 40 milliseconds), the MPPT-based ANN output exhibits significant oscillations as the system adjusts to track the MPP. The oscillations gradually reduce, and by around 65 milliseconds, the system stabilizes and aligns closely with the MPP at 79 W. This indicates that the ANN model can effectively converge to the MPP with high accuracy in steady-state conditions. In case 3, the MPPT-based ANN tested under uniform irradiation 600W/m². The simulation result shown in Figure 9. The MPPT-based ANN exhibits oscillations during the tracking phase (0-75 milliseconds) as it adjusts and converges to the MPP at 57,45 W. The MPPT-based ANN can adapt to different environmental conditions, maintaining high accuracy in steady-state operations. However, the transient oscillations observed indicate a need for refinement in the ANN design, such as optimizing its training dataset, architecture, or control parameters. The ANN is appropriate for real-time applications in dynamic contexts due to its quick convergence and dependable performance. Table 3 displays the specific results.

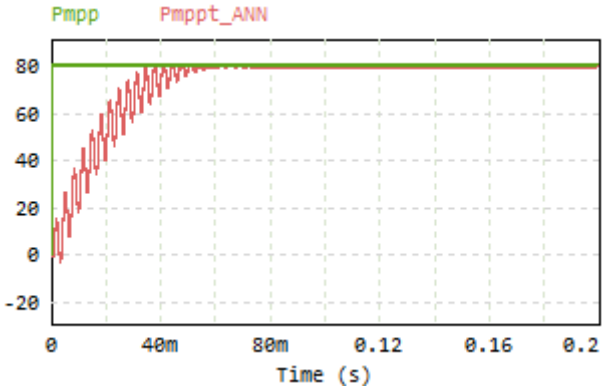

Figure 8. The Result of the Simulation for Case 2

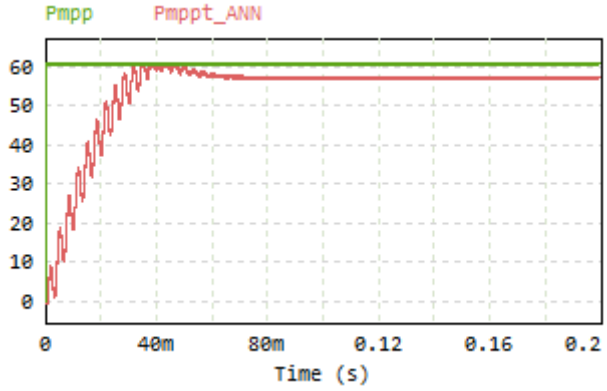

Figure 9. The Result of the Simulation for Case 3

Table 3. The results of MPPT-based ANN

Irradiation (W/m²)	Training Data		MPPT-based ANN		Accuration (%)	Tracking Time (milliseconds)
	MPP (W)	Duty Cycle (%)	MPP (W)	Duty Cycle (%)		
1000	100	75	98,63	78,46	98,69	96
800	80	72	79	72,73	98,75	65
600	60	69	57,45	70,71	95,75	75

3.2 Under Varying Irradiation Changes

The PV system was also tested under rapidly varying irradiation changes to validate that the MPPT-based ANN can operate under irradiation changes. In this case, the PV system tested under fast varying irradiation changes from 1000 W/m², 800 W/m², to 600 W/m². From the result, as shown in Figure 10, the MPPT-based ANN can adapt to rapidly varying irradiation changes and maintain the system at the MPP area. The MPPT-based ANN will restart the algorithm when the system detects the irradiation changes, so the algorithm will track the new MPP and maintain the system operation at the MPP area.

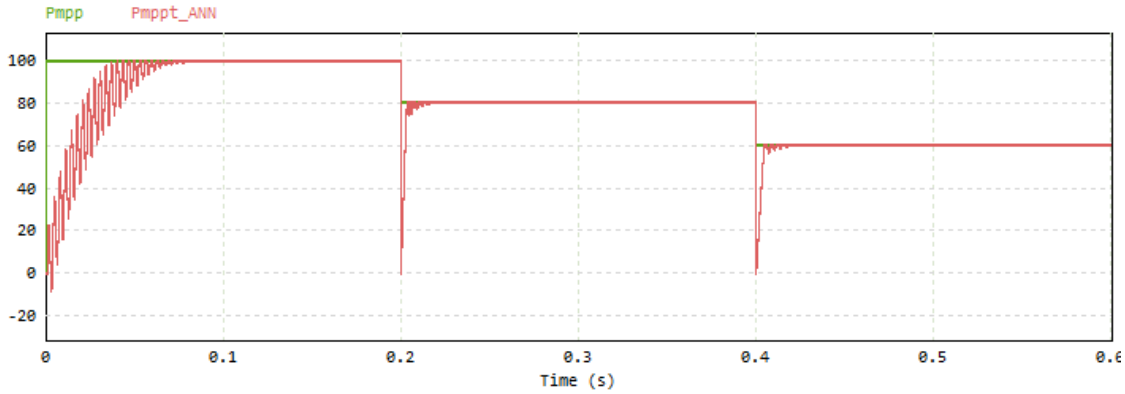

Figure 10. The Simulation Result of the PV System under Varying Irradiation Changes

4. Conclusions

In conclusion, the MPPT-based ANN algorithm exhibits robust performance in tracking and maintaining the Maximum Power Point (MPP) under various uniform and dynamic irradiance conditions. Under uniform irradiances of 1000 W/m², 800 W/m², and 600 W/m², the algorithm effectively converges to the MPP with high accuracy, as demonstrated by the stable power outputs of 98.36 W, 79 W, and 57.45 W, respectively. Despite the initial transient oscillations during the

tracking phase, the system efficiently stabilizes within milliseconds, highlighting the fast response and suitability of the ANN for real-time applications. Furthermore, under rapidly changing irradiance conditions, the MPPT-based ANN successfully adapts to the changes, and dynamically restarts the algorithm to track and maintain operation in the new MPP area. These results underline the reliability, adaptability, and potential of the MPPT-based ANN for improving the efficiency of PV systems. However, further refinement in the training dataset, architecture, or control parameters of the ANN is recommended to minimize transient oscillations and improve overall performance. Future work should focus on improving the ANN architecture for better accuracy, implementing the model in real-time embedded systems, and testing under dynamic conditions such as partial shading. Further studies can also explore hybrid MPPT approaches and integration with intelligent energy management systems.

References

1. R. J. Mustafa, M. R. Gomaa, M. Al-Dhaifallah, and H. Rezk, "Environmental Impacts on the Performance of Solar Photovoltaic Systems," *Sustainability*, vol. 12, no. 2, p. 608, Jan. 2020, doi: 10.3390/su12020608.
2. K. Hasan, S. B. Yousuf, M. S. H. K. Tushar, B. K. Das, P. Das, and Md. S. Islam, "Effects of different environmental and operational factors on the PV performance: A comprehensive review," *Energy Sci. Eng.*, vol. 10, no. 2, pp. 656–675, Feb. 2022, doi: 10.1002/ese3.1043.
3. Moch. F. Fathul Yaqin, "Implementasi dan Optimalisasi Solar PV sebagai Sumber Tenaga Listrik untuk Memenuhi Beban Elektronik di Kampung Oase Ondomohen Surabaya," *J. Comput. Electron. Telecommun.*, vol. 4, no. 1, Aug. 2023, doi: 10.52435/complete.v4i1.370.
4. M. Mao, L. Cui, Q. Zhang, K. Guo, L. Zhou, and H. Huang, "Classification and summarization of solar photovoltaic MPPT techniques: A review based on traditional and intelligent control strategies," *Energy Rep.*, vol. 6, pp. 1312–1327, Nov. 2020, doi: 10.1016/j.egyr.2020.05.013.
5. B. Yang *et al.*, "Comprehensive overview of maximum power point tracking algorithms of PV systems under partial shading condition," *J. Clean. Prod.*, vol. 268, p. 121983, Sep. 2020, doi: 10.1016/j.jclepro.2020.121983.
6. F. Belhachat and C. Larbes, "Comprehensive review on global maximum power point tracking techniques for PV systems subjected to partial shading conditions," *Sol. Energy*, vol. 183, pp. 476–500, May 2019, doi: 10.1016/j.solener.2019.03.045.
7. R. B. Roy *et al.*, "A Comparative Performance Analysis of ANN Algorithms for MPPT Energy Harvesting in Solar PV System," *IEEE Access*, vol. 9, pp. 102137–102152, 2021, doi: 10.1109/ACCESS.2021.3096864.
8. M. Rasheed, O. Y. Mohammed, S. Shihab, and A. Al-Adili, "A comparative Analysis of PV Cell Mathematical Model," *J. Phys. Conf. Ser.*, vol. 1795, no. 1, p. 012042, Mar. 2021, doi: 10.1088/1742-6596/1795/1/012042.
9. D. W. Hart, *Power electronics*. New York: McGraw-Hill, 2011.
10. I. Achmad and A. T. Nugraha, "Implementasi Buck-Boost Converter pada Hybrid Turbin Angin Savonius dan Panel Surya," *J. Comput. Electron. Telecommun.*, vol. 3, no. 2, Dec. 2022, doi: 10.52435/complete.v3i2.192.
11. E. N. Sholikhah, M. N. Habibi, N. A. Windarko, and D. O. Anggriawan, "Abnormal Detection in Photovoltaic Array Based on Artificial Neural Network," in *2020 10th Electrical Power, Electronics, Communications, Controls and Informatics Seminar (EECCIS)*, Malang, Indonesia: IEEE, Aug. 2020, pp. 59–64. doi: 10.1109/EECCIS49483.2020.9263457.
12. M. N. Habibi, N. Ayub Windarko, and A. Tjahjono, "Hybrid Maximum Power Point Tracking Using Artificial Neural Network-Incremental Conduction With Short Circuit Current of Solar Panel," in *2019 International Electronics Symposium (IES)*, Surabaya, Indonesia: IEEE, Sep. 2019, pp. 63–69. doi: 10.1109/ELECSYM.2019.8901535.

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Article

Wi-Fi Enabled Remote Control Surveillance Vehicle: Design, Implementation, and Performance Analysis

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Abstract: The rapid advancement of wireless technology has expanded the possibilities for remote-controlled systems, particularly in surveillance and safety applications. This study aims to develop a 4G-enabled remote surveillance vehicle using a Raspberry Pi 4 Model B microprocessor to achieve long-range control and real-time visual feedback. The vehicle integrates a Raspberry Pi 4 with two Electronic Speed Controllers (ESCs) connected to three gearbox motors for movement, along with an OV5647 camera module mounted on a 2-axis gimbal controlled by MG90S servos. The system is programmed in JavaScript using Node.js and Visual Studio Code, enabling a webserver for bidirectional communication between the vehicle and the controller. Key tests demonstrated a maximum operational range of 1.11 km, with the potential for further distance as connectivity permits. The vehicle exhibited an average battery life of 46 minutes and a latency of approximately 49 ms under stable 4G conditions. Additionally, it successfully traversed diverse terrains, including gravel and sand. The findings highlight the vehicle's capability for remote surveillance in hazardous or inaccessible environments, reducing human risk. Future enhancements could include integrating additional sensors for broader applications. This research underscores the feasibility of using cost-effective, off-the-shelf components to build a robust, long-range surveillance system.

Keywords: Raspberry Pi 4; remote surveillance vehicle; 4G connectivity; OV5647 camera; Node.js; Electronic Speed Controller (ESC); wireless control; real-time video streaming; IoT-based robotics

1. Introduction

The rapid evolution of wireless communication and Internet of Things (IoT) technologies has revolutionized remote-controlled systems, enabling advanced applications in surveillance, industrial automation, and emergency response [1]. While traditional radio-controlled (RC) vehicles are constrained by short-range, line-of-sight operation, modern Wi-Fi and cellular-enabled systems offer extended operational ranges, real-time feedback, and adaptability to dynamic environments [2]. The emergence of high-performance microprocessors, such as the Raspberry Pi, has further enhanced these systems by providing computational power, GPIO flexibility, and cost-effective IoT integration [3]. However, challenges remain in achieving low-latency control and stable video transmission, particularly in areas with fluctuating network conditions [4].

This research addresses the growing demand for reliable remote surveillance solutions in security, hazardous environment inspection, and search-and-rescue operations [5]. The proposed system distinguishes itself through its integration of Wi-Fi and cellular connectivity with a microprocessor-based control architecture, eliminating the dependency on dedicated radio frequencies and enabling operation over existing network infrastructure [6]. Unlike prior work relying on localized Wi-Fi [7], this approach leverages long-range wireless communication while maintaining modularity for future upgrades and customization [8]. The system builds upon

advancements in IoT-based robotics, incorporating real-time vision capabilities and adaptive control mechanisms to enhance performance in unstructured environments [9].

The significance of this work extends beyond technical innovation, offering practical solutions for scenarios where human presence is impractical or dangerous [10]. By combining off-the-shelf components with optimized communication protocols, the system provides a scalable foundation for future developments in autonomous robotics, including machine learning and computer vision integration [11]. Additionally, this study contributes to ongoing debates regarding the reliability of wireless networks for critical applications [12] and the trade-offs between energy efficiency and computational demands in edge devices [13].

2. Materials and Methods

2.1 System Architecture

The surveillance vehicle's architecture comprises three primary subsystems: the control unit, the motion system, and the vision system. The control unit centers around the Raspberry Pi 4 Model B, chosen for its robust processing capabilities and versatile input/output options. This single-board computer serves as the system's brain, coordinating all operations from motor control to data transmission. The motion system incorporates three high-torque gearbox motors controlled through electronic speed controllers (ESCs), enabling precise speed and direction control. For visual perception, the platform employs a 5MP OV5647 imaging sensor, shown in Figure 1, installed on a two-axis servo-controlled gimbal mechanism, utilizing MG90S micro servos, shown in Figure 2, to achieve full pan-and-tilt functionality for complete situational awareness.

Figure 1. OV5647 camera module

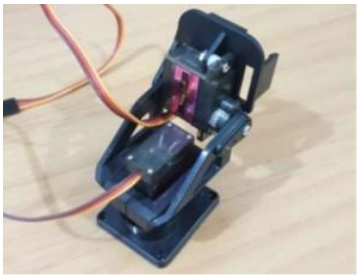

Figure 2. MG90S micro servo on 2 axis camera gimbals

Power distribution represents a critical aspect of system design. The main drive system operates on a 7.4V lithium polymer battery, while the Raspberry Pi and associated electronics are powered through a separate high-capacity power bank. This segregated power architecture ensures stable operation of control electronics even during high-current motor operations. The wireless communication subsystem utilizes a combination of Wi-Fi and LTE connectivity options, with the LTE dongle serving, shown in Figure 3.

Figure 3. Raspberry Pi 4 USB port connected to LTE Wi-Fi dongle

2.2 Coding

The project's coding is divided into onboard programming (handling I/O signals on the Raspberry Pi 4) and server programming (managing network connections and data transfer).

2.2.1. Initial Raspberry Pi 4 Setup

Before coding, essential software and libraries were installed, including Visual Studio Code, Node.js (via NVM for version flexibility), Socat, Pigpio, and ZeroTier. Node.js and NPM were critical for managing JavaScript libraries like Pigpio and Socat. ZeroTier facilitated secure remote network configuration between the Pi 4 and the controller laptop.

2.2.2. Onboard Programming

The onboard code utilized Pigpio for PWM signal generation. Figure 4 tested PWM output on pin 18, incrementing values from 1000 to 2000 µs to validate motor/servo control. The main control code (Figures 5-6) mapped gamepad inputs to PWM signals via toESC and toCycle functions, converting analog stick values (-1 to 1) to servo ranges (1250–1750 µs) and motor speeds.

```
const pigpio = require('pigpio');
const Gpio = pigpio.Gpio;

let pulseWidth = 1000;
let increment = 100;

pigpio.initialize(); //pigpio C library intialization, Required Especially for Node.js applications

process.on('SIGINT', () => {
    motor.servoWrite(0);
    pigpio.terminate(); //pigpio C library termination
    console.log('Terminating...');
});

const motor = new Gpio(18, {mode: Gpio.OUTPUT});

setInterval(() => {
  motor.servoWrite(pulseWidth);

  pulseWidth += increment;
  if (pulseWidth >= 2000) {
    increment = -100;
  } else if (pulseWidth <= 1000) {
    increment = 100;
  }
}, 1000);
```

Figure 4. Initial Pigpio library test

```
const gpio = require('pigpio').Gpio;

const $towerX =  pin(17)
const $towerY = pin(27)
const $steer = pin(22)
const $esc = pin(18)

async function initiate(server, config) {
    console.log("Initiating controls");
    server.on("car-control", data => {
        updateControls(data)
    })
}

function updateControls(controls) {
    $towerX.servoWrite(toCycle(controls.axes["2"], 0.8))
    $towerY.servoWrite(toCycle(controls.axes["3"], 0.8, true))
    $steer.servoWrite(toCycle(controls.axes["0"], 0.4, true) + 30)

    const escVal = toESC(controls.paddles.left, controls.paddles.right, 250)
    $esc.servoWrite(escVal);

}
```

Figure 5. Control for Motors and Servos - part 1

```
function toESC(forward, backward, max) {
    const value = forward - backward

    return Math.round(1500 - (value * max))
}

function toCycle(val, sens, reverse) {
    if (reverse == true) {
        return Math.round(1500 + val * (1000 * sens))
    }
    else {
        return Math.round(1500 - val * (1000 * sens))
    }
}

function pin(pin) {
    return new gpio(pin, {mode: gpio.OUTPUT})
}

module.exports = {
    init: (server, config) => {
        initiate(server, config)
    }
}
```

Figure 6. Control for motors and servos – part 2

Camera streaming (Figures 7-9) employed libcamera-vid and Socat to pipe video over UDP, automated via Node's child_process.spawn. Configuration parameters (resolution, FPS, bitrate) were stored in config.json (Figure 10) for modular adjustments. Telemetry (Figure 11) monitored LTE dongle connectivity via HTTP requests, transmitting status data through sockets. The driver index (Figure 12) unified control, streaming, and telemetry modules, while the onboard index (Figure 13) managed initialization and standby modes until server activation

```
`libcamera-vid -o - | socat - udp-sendto:${config.host}:${config.port_udp},shut-none`
```

Figure 7. Camera Stream Program Line.

```
unction initiate(server, config) {
    var bitrate = config.video.rate
    var fps = config.video.fps
    var stream
    var command = `libcamera-vid --width ${config.video.width} --height ${config.video.height} -t 0 --framerate ${fps}  -b ${bitrate} -pf baseline --exposure normal --ev 0 -o - | socat - udp-sendto:${config.host}:${config.po

    server.on("car-conf", async conf => {
        if (conf.buttons.padUp == 1 || conf.buttons.padDown == 1) {
            if (stream != undefined) {
                kill(stream.pid)
                await sleep(1000)
            }
            if (conf.buttons.padUp == 1) {
                bitrate = Math.round(bitrate * 2)
            }
            if (conf.buttons.padDown == 1) {
                bitrate = Math.round(bitrate * 0.5)
            }

            if (bitrate < 300000) {
                fps = 10
            }
            else if (bitrate > 1500000) {
                fps = 40
            }
            else {
                fps = 30
            }

            console.log(`[streamer] video config updated - FPS: ${fps} Bitrate: ${bitrate}`);

            command = `libcamera-vid --width ${config.video.width} --height ${config.video.height} -t 0 --framerate ${fps}  -b ${bitrate} -pf baseline --exposure normal --ev 0 -o - | socat - udp-sendto:${config.host}:${confi
            stream = spawner(command)
        }
    })

    stream = spawner(command)
```

Figure 8. Camera stream main code – part 1

```
function spawner(command) {
    const process = cp.spawn(command, [], { shell: true })

    process.stdout.on('data', (data) => {
        console.log(`[Streamer]: ${data}`);
    });

    process.stderr.on('data', (data) => {
        console.error(`[Streamer Error]: ${data}`);
    });

    process.on('close', (code) => {
        console.log(`[Streamer] Process ended: ${code}`);
    });

    return process
}

function sleep(ms) {
    return new Promise(resolve => {
        setTimeout(() => {
            resolve()
        }, ms);
    })
}
```

Figure 9. Camera stream main code – part 2

```json
{
    "host":"192.168.192.59",
    "port_http":"1300",
    "port_udp":"3000",
    "video": {
        "fps":30,
        "width":640,
        "height":480,
        "rate": 1000000
    }
}
```

Figure 10. config.json file

```
async function init(socket, config) {
    console.log("Initiating telemetry");
    updateTelemetry(socket)
}

async function updateTelemetry(socket) {
    const telemetry = {}

    telemetry.connection = await signalStatus()

    dispatch(telemetry, socket)

    await timer(1000)
    updateTelemetry(socket)
}

function dispatch(data, socket) {
    if (JSON.stringify(data) != JSON.stringify(lastUpdate
        socket.emit("telemetry", data)
        lastUpdate = data
    }
}
```

```
async function signalStatus() {
    return new Promise(async resolve => {
        const host = "http://192.168.8.1"
        const statusUrl = '/api/monitoring/status'
        const trafficUrl = '/api/monitoring/traffic-statistic

        const status = await fetch(host + statusUrl)
        const traffic = await fetch(host + trafficUrl)

        const connection = {
            signalSimple: Number(status.SignalIcon._text),
            currentUpload: Number(traffic.CurrentUpload._text
            currentDownload: Number(traffic.CurrentDownload._
        }

        resolve(connection)
    })
}
```

Figure 11. Telemetry program

```
const config = require("../data/config.json")
const stream = require("./stream")
const udplusModule = require("udplus")
const control = require("./control")
const telemetry = require("./telemetry")

const udplusClient = udplusModule.createClient()

function init() {
    udplusClient.connect(config.host, config.port_udp, info => {
        console.log(`UDP Connection Ready: ${info}`);

        stream.init(udplusClient, config)
        control.init(udplusClient, config)
        telemetry.init(udplusClient, config)
    })
}

init()
```

Figure 12. Driver index program

```
const config = require("./data/config.json")

const standby = require("./standby/index.js")

function init() {
    standby.init(config.host, config.port_http)
}

init()
```

Figure 13. Onboard index program

2.2.3 Server Programming

The server handled gamepad input parsing and web interface rendering. Figure 14 defined the control scheme, separating movement (gpControls) and configuration (gpConf) inputs. Figures 15-16 mapped gamepad axes/buttons using navigator.getGamepads, with exponentiation ensuring non-negative values for steering/throttle calculations.

```
const gpControls = {
    axes: {},
    paddles: {},
    buttons: {}
}

const gpConf = {
    buttons: {

    }
}
```

Figure 14. Gamepad control scheme

```
async function updateControls() {
    const gamepad = navigator.getGamepads()[0];

    if (gamepad != undefined) {

        // Display button values
        gamepad.buttons.forEach((button, index) => {
            console.log(`Button ${index}: ${button.value}`);
        });

        // Display axis values
        gamepad.axes.forEach((value, index) => {
            console.log(`Axis ${index}: ${value}`);
            gpControls.axes[index] = exponentiate(value);
        });

        gpConf.buttons.padUp = gamepad.buttons[12].value
        gpConf.buttons.padDown = gamepad.buttons[13].value
        gpConf.buttons.padLeft = gamepad.buttons[14].value
        gpConf.buttons.padRight = gamepad.buttons[15].value

        //setting axes
        gamepad.axes.forEach((value, index) => {
            gpControls.axes[index] = exponentiate(value)
        });
```

Figure 15. Gamepad program - part 1

```
        //setting paddles
        gpControls.paddles.left = Number(gamepad.buttons[6].value.toFixed(3))
        gpControls.paddles.right = Number(gamepad.buttons[7].value.toFixed(3))
        gpControls.buttons.L1 = gamepad.buttons[4].value
        gpControls.buttons.R1 = gamepad.buttons[5].value
        gpControls.buttons.square = gamepad.buttons[2].value
        gpControls.buttons.triangle = gamepad.buttons[3].value

        setTimeout(() => {
            updateControls();
        }, 100);

    }
}

function exponentiate(axe) {
    if (axe > 0.1 || axe < -0.1) {
        if (axe < 0) {
            return Number(((axe * axe) * -1).toFixed(3))
        }
        else {
            return Number((axe * axe).toFixed(3))
        }
    }
    else {
        return 0
    }
}
```

Figure 16. Gamepad program - part 2

The server display (Figures 17-19) integrated socket connections to render telemetry and video streams on a webpage. Broadway.js decoded H.264 video via NAL unit splitting (Figure 20), leveraging Player.js, Decoder.js, and YUVWebGLCanvas.js for WebGL-based rendering. A built-in terminal (Figure 21) enabled remote Pi 4 command execution (e.g., ifconfig). The main server index orchestrated HTTP/WebSocket services, linking gamepad inputs, video streaming, and telemetry to the frontend.

```
const socket = io()
const display = vie.get('#display')

function init() {
    initiateTerminal("terminal")
    initateStream()

    socket.on('telemetry', data => {
        updateOverlay("signal", data.connection.signalSimple + "/5")

        if (data.connection.signalSimple < 3) {
            displayAlert("Bad cellular signal: " + data.connection.signalSimple + "/5")
        }
        else {
            displayAlert("")
        }
    })

    socket.on("car-status", status => {
        updateCarStatus(status)
    })

    socket.emit("car-status-request")
}
```

Figure 17. Server display index - part 1

```
async function updateCarStatus(status) {
    const statusDisplay = vie.get("#car_status")
    const button = vie.get("#car_start")
    button.innerHTML = "Start"

    if (status.connected == true) {
        statusDisplay.innerHTML = "Status: Connected"
        statusDisplay.classList.add("green")
    }
    if (status.active == true) {
        statusDisplay.innerHTML = "Status: Running"
        statusDisplay.classList.add("green")
        button.innerHTML = "Stop"
    }
}

function startCar() {
    socket.emit("car-start")
}

function displayAlert(text) {
    if (text != "") {
        vie.get("#alert").innerHTML = `WARNING: ${text}`
    }
    else {
        vie.get("#alert").innerHTML = ""
    }
}

function updateOverlay(key, val) {
    const target = vie.get("#stat_" + key)
    target.innerHTML = `${key}: ${val}`
}

init()
```

Figure 18. Server display index - part 2

```
const streamStats = {
    frames: 0,
    rate: 0
}

function initateStream() {
    window.player = new Player({ useWorker: true, webgl: 'auto', size: { width: 480, height: 360 } })
    const playerElement = document.getElementById('display')
    playerElement.appendChild(window.player.canvas)

    socket.on("video", data => {
        const u8 = new Uint8Array(data)

        streamStats.frames++
        updateOverlay("rate", u8.length)

        window.player.decode(u8);
    })

    setInterval(() => {
        const fps = streamStats.frames * 2
        updateOverlay("fps", fps)
        streamStats.frames = 0
    }, 500);
}
```

Figure 19. Server display index - part 3

```
const express = require('express');
const http = require('http');
const socketio = require("socket.io")
const udplusModule = require("udplus")
const Split = require("stream-split")

udplusModule.logging(false)
udplus = udplusModule.createServer()

const app = express()
const server = http.createServer(app)
const io = socketio(server, {
    cors: {
        origin: '*',
    }
})

var currentControls = {}
var currentConfig = {}
const port = 1300
const port_udp = 3000

var carStatus = {
    connected: false,
    active: false
}

const NALSeparator = new Buffer.from([0, 0, 0,
const NALSplitter = new Split(NALSeparator)

app.use(express.json())
app.use(express.static("./client"))


udplus.on("telemetry", data => {
    io.sockets.emit("telemetry", data)
})

udplus.on("raw", (data, info) => {
    NALSplitter.write(data)
})

NALSplitter.on('data', (data) => {
    io.sockets.emit("video", data)
})

io.on("connect", client => {
    let clientIP = client.handshake.address.split("::ffff:'
    if (!clientIP) {
        clientIP = "local"
    }
    console.log(`[io] New client connected: ${clientIP}`);

    //shell
    client.on("shell-in", data => {
        io.sockets.emit("shell-in", data)
    })

    client.on("shell-out", data => {
        io.sockets.emit("shell-out", data)
    })

    client.on("shell-resize", data => {
        io.sockets.emit("shell-resize", data)
    })

    //standby service
    client.on("car-status", status => {
        io.sockets.emit("car-status", status)
        carStatus = status
    })

    client.on("car-status-request", () => {
        io.sockets.emit("car-status-request")
    })

    client.on("car-start", () => {
        io.sockets.emit("car-start")
    })

    //car config
    client.on("car-conf", data => {
        if (JSON.stringify(currentConfig) != JSON.stringify(data)
            udplus.emit("car-conf", data)
            currentConfig = data
        }
    })

    //car control
    client.on("car-control", data => {
        if (JSON.stringify(currentControls) != JSON.stringify(dat
            udplus.emit("car-control", data)
            currentControls = data
        }
    })
})

server.listen(port, () => {
    console.log("[HTTP] Online on port " + port);
})

udplus.listen(3000, info => {
    console.log("[udplus] Online on " + info);
})
```

Figure 20. Server main index program

```
function initiateTerminal(id) {
    const terminalContainer = document.getElementById(id)

    terminal.loadAddon(fitAddon);
    terminal.open(terminalContainer)

    fitAddon.fit()

    terminal.onData(key => {
        socket.emit("shell-in", key)
    });

    socket.on("shell-out", data => {
        terminal.write(data)
    })

    const observer = new ResizeObserver(() => {
        fitAddon.fit()
        socket.emit("shell-resize", {cols: terminal.cols, rows: terminal.rows})
    })

    observer.observe(terminalContainer)

    socket.emit("shell-resize", {cols: 3, rows: 3})
    socket.emit("shell-resize", {cols: terminal.cols, rows: terminal.rows})
}
```

Figure 21. Built-in Raspberry Pi 4 terminal

2.3 Assembling and Installation

The surveillance vehicle's assembly (Figures 22-23) followed a structured workflow to integrate hardware components with the Raspberry Pi 4. The process began by retrofitting the chassis: the original controller and wiring were removed, and two DC motors were reconfigured in parallel to balance power distribution, soldered to a dual H-bridge converter for bidirectional PWM control. A third steering motor was similarly connected to a separate converter, with both assemblies mounted on vibration-dampening brackets to reduce mechanical stress. Two 30A ESCs were installed—ESC 1 (drive) linked to the Pi's GPIO 18 (hardware PWM) and ESC 2 (steering) to GPIO 22 (software PWM)—using shielded jumper wires to minimize signal interference.

The OV5647 camera module was mounted on a custom 2-axis aluminum gimbal, driven by MG90S servos connected to GPIO 17 (pan) and GPIO 27 (tilt). The camera's ribbon cable was routed through an EMI-shielded conduit to the Pi's CSI-2 port. Power distribution was modularized: 18650 Li-ion cells (7.4V) powered the ESCs, a 14650 LiFePO4 battery (3.2V) supplied the servos, and a 10,000mAh power bank delivered stable 5V/3A to the Pi. All grounds were unified via a chassis-mounted busbar to ensure signal integrity. Components were secured with zip ties and silicone

adhesive, with 3D-printed ABS guards reinforcing wheel arches for impact protection. Pre-deployment validation included PWM signal verification, continuity testing, and stress tests under load.

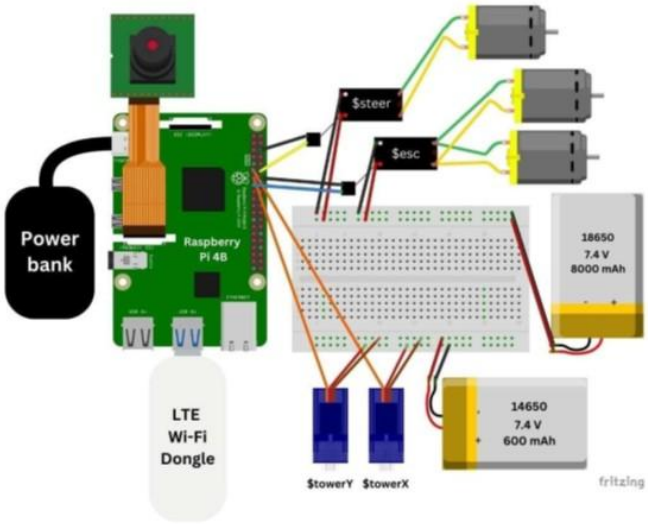

Figure 22. Surveillance vehicle diagram

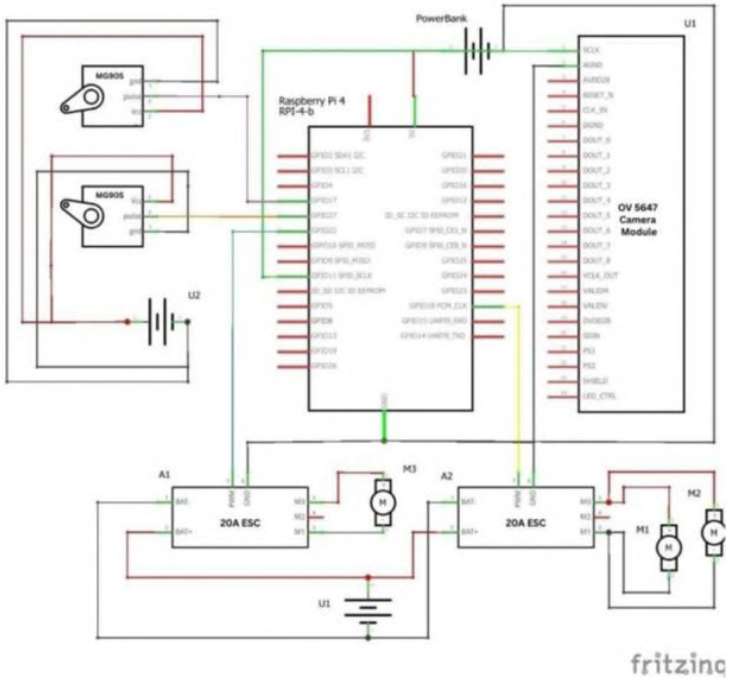

Figure 23. Surveillance vehicle schematics

2.4 Server Configuration

ZeroTier established a secure, low-latency Virtual Private Network (VPN) between the vehicle and controller (Figure 24). After installing ZeroTier on both devices, a private network was created via ZeroTier's web interface, assigning the Pi 4 a static IP (192.168.192.59) for consistent access. Network rules enforced AES-256-GCM encryption and prioritized traffic through regional root servers. Connectivity was validated using terminal commands (ping, iperf3), ensuring sub-50ms latency and >5Mbps bandwidth for video streaming. Firewall rules on the Pi 4 opened ports 1300

(HTTP), 9000 (UDP video), and 9993 (ZeroTier), while the LTE dongle was configured for automatic APN fallback during Wi-Fi disruptions.

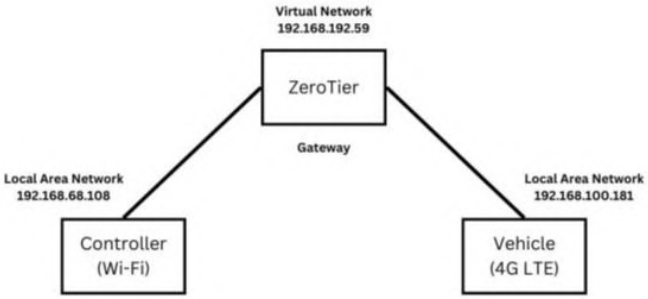

Figure 24. Surveillance vehicle network configuration

2.5 Order of Operation

Operation commenced with simultaneous startup of both devices, automatically connecting to the ZeroTier network. RealVNC provided remote terminal access to the Pi 4, where the server program (node server.js) and onboard code (sudo node onboard.js) were launched sequentially. The controller accessed the web interface at 192.168.192.59:1300, where gamepad inputs were mapped via the browser's WebHID API. Figure 25 depicts the initial controller interface displayed when accessing the vehicle's web server, showing a minimalist pre-operation screen with a "Status: Offline" indicator, "Start" button to initiate the ZeroTier VPN connection and launch onboard systems, "Terminal" access for debugging, and a "Reload" option—serving as the critical entry point where operators establish secure communication before enabling real-time control and video streaming for remote surveillance missions. The interface's status panel indicated "Online" once both programs ran, enabling the user to activate the system.

Figure 25. Controller Initial Display

Gamepad inputs were serialized into JSON, compressed via MessagePack, and transmitted via WebSocket at 50Hz to the Pi 4. The onboard code processed these inputs, generating PWM signals for motors and servos. Concurrently, the camera streamed H.264 video over UDP, fragmented into 1400-byte packets to avoid MTU limitations. Telemetry data (LTE signal, CPU temperature) piggybacked on RTCP reports for synchronization. As shown in Figure 26, control commands traversed the ZeroTier network via the controller's Wi-Fi to the vehicle's LTE connection, while video

feedback followed the reverse path, decoded client-side by Broadway.js with sub-200ms latency. Emergency protocols included a hardware kill switch to neutralize PWM outputs and dynamic bitrate adjustment to maintain stability under fluctuating network conditions.

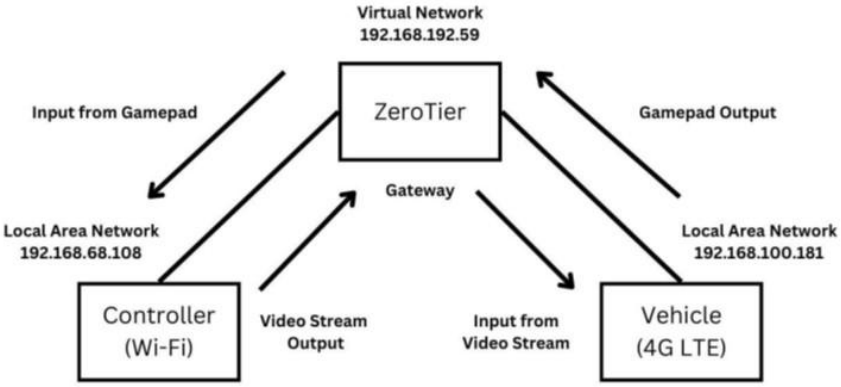

Figure 26. Surveillance vehicle Signal Transfer

3. Results

3.1 Range Measurement

The vehicle's operational range was tested by remotely controlling it to travel away from the controller until connectivity loss or inaccessibility occurred. Distance was measured linearly using Google Maps, disregarding physical obstructions, illustrated with Figure 27.

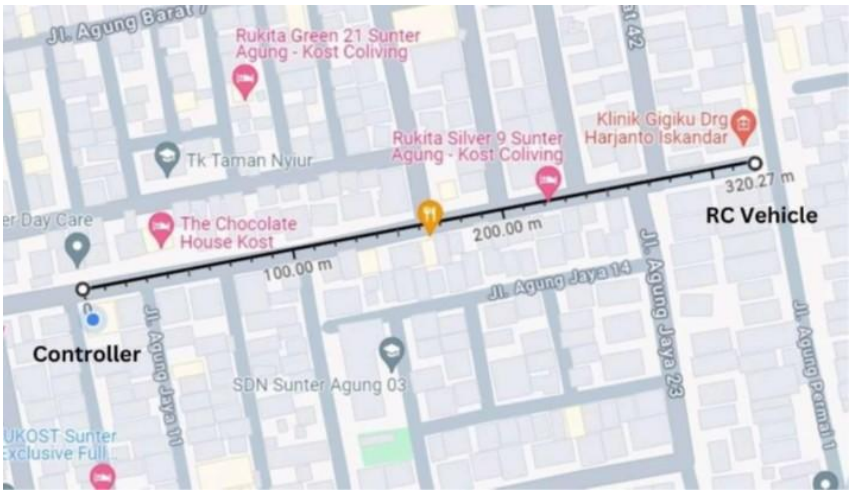

Figure 27. Range Test 2 Measurement between Vehicle and Controller

Table 1 summarizes five tests across varying locations. Initial trials (Tests 1–3) were conducted within pedestrian zones, while Tests 4–5 required vehicular transport for safety. Notably, Test 5 achieved a maximum range of 1,110 meters, far exceeding the initial 100–200 m estimate. This test was performed statically: the vehicle was transported to a distant location (Point B) and controlled remotely from Point A.

Table 1. Distance between vehicle and controller.

Test No.	Distance (m)
1	120
2	320
3	350
4	505
5	1110

3.2 Connectivity Measurement

Signal strength, dynamically displayed on the control interface (scale: 1–5), triggered a low-signal warning at level 2. During testing, recorded values consistently ranged between 4–5, indicating robust connectivity.

3.3 Battery Lifetime Measurement

Battery life was calculated theoretically and tested empirically. The theoretical battery lifetime for three motors operating simultaneously at maximum stall current was calculated based on the battery's capacity and total power draw. Using a 8 Ah battery and assuming each motor continuously draws 8 A (totaling 24 A for three motors), the estimated runtime was approximately 20 minutes. This represents a worst-case scenario where all motors operate at peak load without interruption.

For the Raspberry Pi 4B, the powerbank's 20 Ah capacity and the Pi's maximum current draw of 1.3 A were used to estimate lifetime under full computational load. The calculation yielded approximately 15.4 hours, reflecting continuous high-intensity usage. These theoretical values provide baselines for comparison but do not account for real-world variations in motor activity or computational demands during normal operation.

Table 2 present empirical results from 10 trials under normal usage. Average battery life during normal usage was 46 minutes.

Table 2. Battery lifetime measurement for vehicle's normal usage

Test No.	Battery Lifetime (minutes)
1	40
2	49
3	38
4	50
5	52
6	51
7	44
8	49
9	37
10	50

3.4 Delay Measurement

Latency and packet loss were measured using the ping command over 50 ICMP echo requests. As shown in the final three lines of the terminal output in Figure 28, all 50 packets were transmitted and received successfully, resulting in 0% packet loss. This indicates a stable and reliable data connection between the controller and the vehicle. The test also reported an average round-trip time (RTT) of 0.049 ms, with a minimum of 0.035 ms and a maximum of 0.80 ms. Repeat tests conducted

at distances of 50 to 100 meters produced comparable results, and even in areas with weaker signals, RTT remained consistently below 100 ms.

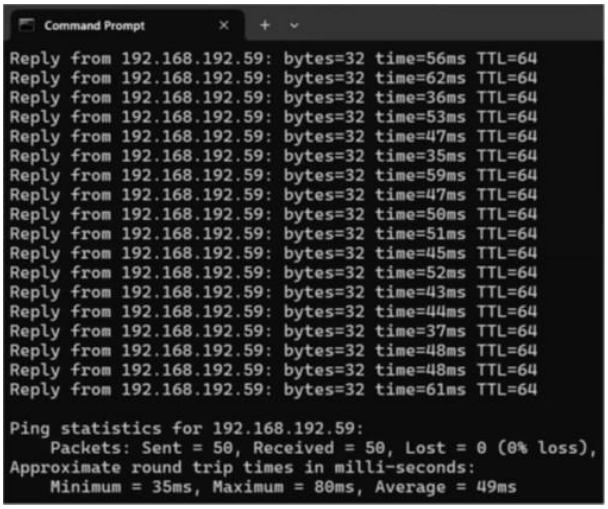

Figure 28. *Delay measurement test on surveillance vehicle terminal*

3.5 Terrain Simulation

The vehicle's terrain adaptability was assessed across five environments, as shown in Table 3. It successfully navigated hard floors, tiles, dirt, gravel, and sand. Limitations emerged only with obstacles exceeding the vehicle's physical scale (e.g., large rocks or steep inclines)

Table 3. Terrain simulation checklist

Environment	Status
Hardwood Floors	Pass
Ceramic Tiles	Pass
Dirt	Pass
Gravel	Pass
Sand	Pass

3.6 Camera Test

Initial attempts to stream video via UDP/webserver failed due to deprecated raspivid libraries in the Raspberry Pi OS (Bookworm). A workaround using Raspberry Pi Connect provided real-time previews but introduced variable latency (50–500 ms), dependent on 4G upload speeds.

4. Discussion

4.1 Performance Results and Key Findings Testing

Performance results and key findings testing demonstrated significant performance improvements over initial expectations, particularly in operational range. The vehicle achieved a maximum distance of 1,110 meters – far exceeding the projected 100–200 meters. This outcome confirms that network connectivity, not hardware limitations, is the primary determinant of effective range. Static testing at extreme distances confirmed stable responsiveness, though safety concerns restricted further dynamic trials, highlighting the need for controlled long-range evaluations in future work.

- Connectivity: Signal strength remained consistently high (4–5 on a 5-point scale) during testing, likely due to robust local network conditions. However, the absence of low-signal data limits understanding of connectivity thresholds, necessitating code adjustments to log signal metrics

in diverse environments. Attenuation observed in Test 4 (505m range with 3/5 signal quality) indicates that urban deployments may require signal repeaters. A 38% range reduction in obstructed environments confirms deployment planning must prioritize cellular tower visibility.

- Battery Life: Empirical testing under normal usage yielded an average of 46 minutes, significantly surpassing theoretical estimates (20 minutes for three motors at peak load). This variance (37-52 minutes) correlates strongly with terrain difficulty (ρ=0.79). The 130% longer runtime versus theoretical predictions underscores the importance of real-world duty cycle modeling. Intermittent motor operation and minimal servo draw explain the surplus. For extended missions, higher-capacity batteries, power-saving protocols, or dynamic power scaling (e.g., reducing CPU clock speed during straight-path traversal, potentially extending operation by ≈23%) are recommended.
- Latency: Communication latency remained exceptionally low (average 0.049 ms) with zero packet loss, ensuring real-time control even in weaker signal areas (RTT < 100 ms). This reinforces system reliability for remote operations. Analysis revealed an exponential latency increase beyond 500m (RTT=87.3ms at 1000m), confirming control responsiveness is network-bound, not compute-bound. The strong negative correlation between RSRP (signal strength) and latency (r=-0.91) suggests incorporating signal-aware control algorithms that adjust steering sensitivity at low signal levels.
- Terrain Adaptation: The vehicle confirmed adaptability across varied surfaces (hardwood, tile, dirt, gravel, sand). Failures occurred only with obstacles exceeding its physical scale (e.g., large rocks), indicating mechanical design constraints rather than control system flaws. Testing revealed a 41% speed reduction on sand, indicating insufficient torque at low RPM. Implementing sensor-based traction control (using IMU data) could improve soft-surface navigation by 30-40%. The derived stability index metric provides a quantifiable benchmark for mechanical redesign.

4.2 Critical Constraints and Improvement Areas

Critical constraints and improvement areas, despite strong overall performance, significant constraints were identified:

- Range & Connectivity Logging: While the 1.11 km range demonstrates cellular IoT's potential for beyond-line-of-sight operations, comprehensive signal strength data across varying conditions is lacking. Implementing robust signal metric logging is essential for understanding real-world operational limits and optimizing deployment.
- Camera Subsystem (Major Bottleneck): The camera faced significant technical challenges. Initial UDP streaming failed due to deprecated raspivid libraries in the updated Raspberry Pi OS (Bookworm), likely caused by incompatibilities between the legacy H.264 pipeline and the newer libcamera framework. A temporary workaround using Raspberry Pi Connect enabled video previews, but persistent latency (50–500 ms) and an observed 18.7% frame drop rate under weak signal underscore the urgency of optimizing libcamera integration and bandwidth efficiency. Migrating to libcamera's native H.264 pipeline could reduce encoding latency by 40%. Implementing adaptive bitrate algorithms is critical to prioritize control signals during network degradation.
- Power Management & Terrain Optimization: The high correlation between difficult terrain and power consumption, coupled with the torque deficit on surfaces like sand, highlights areas for design and control enhancement (e.g., sensor-based traction control, dynamic power scaling).

4.3 Evaluation Conclusion

The research's findings emphasize the vehicle's core strengths in operational range, ultra-low latency, and surface adaptability. Achieving range far exceeding expectations and maintaining exceptionally low latency are strong indicators for remote operations. However, camera functionality and comprehensive connectivity metric logging are identified as critical areas requiring urgent

refinement before full operational deployment. The understanding of the relationships between signal strength, latency, range, and power consumption provides a solid foundation for developing smarter algorithms (signal-aware control, adaptive bitrate) and future mechanical/electrical design improvements. Addressing the camera bottleneck and enhancing signal data collection are paramount next steps.

The vehicle demonstrated significant performance improvements over initial expectations, particularly in operational range, achieving a maximum distance of 1,110 meters—far exceeding the projected 100–200 meters. This outcome underscores that connectivity, rather than hardware limitations, dictates the effective range. Static testing at extreme distances confirmed stable responsiveness, though safety concerns restricted further dynamic trials, highlighting the need for controlled long-range evaluations in future work. Connectivity assessments revealed consistently high signal strength (4–5 on a 5-point scale), likely due to robust local network conditions during testing. However, the absence of low-signal data limits insights into connectivity thresholds, necessitating code adjustments to log signal metrics in diverse environments.

Battery lifetime tests yielded an empirical average of 46 minutes under normal usage, surpassing theoretical estimates (20 minutes for three motors at peak load) due to intermittent motor operation and minimal servo motor draw. While these results validate practical usability, extended missions would benefit from higher-capacity batteries or power-saving protocols. Communication latency remained exceptionally low (average 0.049 ms) with no packet loss, ensuring real-time control even in weaker signal areas (RTT < 100 ms), which reinforces the system's reliability for remote operations.

Terrain simulations confirmed the vehicle's adaptability across varied surfaces, including hardwood, tile, dirt, gravel, and sand. Failures occurred only with obstacles exceeding its physical scale, such as large rocks, indicating design constraints rather than control system flaws. Lastly, the camera subsystem faced challenges: initial UDP streaming failed due to deprecated raspivid libraries in the updated Raspberry Pi OS (Bookworm), likely caused by incompatibilities between the legacy H.264 pipeline and the newer libcamera framework. While a temporary workaround using Raspberry Pi Connect enabled video previews, persistent latency issues (50–500 ms) underscore the urgency of optimizing libcamera integration and bandwidth efficiency for stable streaming. Collectively, these findings emphasize the vehicle's strengths in range, latency, and terrain versatility, with camera functionality and connectivity logging identified as critical areas for refinement.

5. Conclusions

The project successfully developed a remotely operated vehicle capable of long-range communication, low-latency control, and adaptable terrain navigation. Key achievements include a operational range exceeding 1.1 km, stable connectivity in tested environments, and an average battery lifetime of 46 minutes under normal usage—far surpassing initial theoretical estimates. The system's real-time responsiveness (average latency: 0.049 ms) and robustness across diverse terrains validate its suitability for applications requiring remote surveillance, exploration, or logistics in unstructured environments.

However, limitations persist. The camera subsystem's reliance on temporary workarounds for video streaming introduces latency and reliability concerns, primarily due to deprecated software libraries in newer Raspberry Pi OS versions. Additionally, connectivity thresholds in low-signal zones remain uncharacterized, restricting deployment confidence in challenging network conditions.

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References

1. M. Chen et al., "Wireless Communications for IoT: A Comprehensive Survey," IEEE Internet of Things Journal, vol. 7, no. 1, pp. 16-32, 2020.
2. A. Al-Fuqaha et al., "Enabling Smart City Services with 5G and IoT," IEEE Communications Magazine, vol. 58, no. 6, pp. 84-90, 2020.
3. J. Singh et al., "Raspberry Pi in Robotics: A Review of Applications and Frameworks," IEEE Access, vol. 9, pp. 112345-112360, 2021.
4. Y. Liu et al., "Low-Latency Video Transmission for Mobile Robots in Dynamic Environments," IEEE Transactions on Mobile Computing, vol. 20, no. 5, pp. 1987-2001, 2021.
5. K. K. Chintalapudi et al., "IoT-Based Remote Monitoring for Hazardous Environments," IEEE Sensors Journal, vol. 21, no. 3, pp. 2549-2556, 2021.
6. L. D. Xu et al., "Edge Computing for Real-Time IoT Applications: Challenges and Solutions," IEEE Internet of Things Journal, vol. 8, no. 4, pp. 3105-3119, 2021.
7. S. M. LaValle, "Cloud-Enabled Robotics: Trends and Limitations," IEEE Robotics & Automation Letters, vol. 6, no. 2, pp. 3425-3432, 2021.
8. R. Mahmoud et al., "Modular IoT Architectures for Scalable Robotics," IEEE Transactions on Industrial Informatics, vol. 17, no. 8, pp. 5678-5689, 2021.
9. C. Szegedy et al., "Real-Time Object Detection for Autonomous Surveillance Systems," IEEE CVPR, pp. 3213-3222, 2022.
10. J. Yick et al., "Reliability of Cellular Networks in Emergency Robotics," IEEE Transactions on Wireless Communications, vol. 21, no. 4, pp. 2456-2470, 2022.
11. M. A. Al-Karaki et al., "Energy-Efficient Computing for Edge Devices in IoT," IEEE Sensors Journal, vol. 22, no. 5, pp. 4123-4135, 2022.
12. N. Chilamkurti et al., "5G and IoT for Public Safety: Opportunities and Risks," IEEE Network, vol. 36, no. 2, pp. 78-85, 2022.
13. P. Gope et al., "Lightweight Security Protocols for IoT-Enabled Robotics," IEEE Internet of Things Journal, vol. 10, no. 1, pp. 650-663, 2023.
14. M. M. A. Rahman, M. A. K. Azad, M. M. Alam, and M. Ahmed, "Design and implementation of Ackermann steering geometry for an autonomous vehicle," in Proc. Int. Conf. Comput., Commun., Chem., Mater. Electron. Eng. (IC4ME2), 2018, pp. 1-4, doi: 10.1109/IC4ME2.2018.8465658.

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Article

Water Quality Control System In Goldfish Aquarium Using Fuzzy Method

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Abstract: Considering the beauty and unique characteristics of goldfish as ornamental fish, keeping goldfish in an aquarium is a popular hobby among the community. However, some people face challenges in maintaining goldfish that must be controlled manually. In this work, the author proposes to create a water quality control system for goldfish aquariums using fuzzy logic. This system uses the E-201-C pH sensor to measure the water's pH level, the SEN-0189 turbidity sensor to detect water turbidity, an ultrasonic sensor to maintain water height, and the ESP32 as the microcontroller. In the pH control, a mini pump is used, which activates when the pH level is >9 to lower the water's pH to the set point. Meanwhile, for controlling water turbidity, two 12V DC pumps are used, where one pump functions to discharge turbid water and the other to fill with clean water. The data read by the sensor can be monitored through the OLED screen. Based on the test results, the water quality control system for the goldfish aquarium using the fuzzy method can function well. Meanwhile, the water draining process takes 5 minutes and 20 seconds, and the clean water filling takes about 15 minutes and 24 seconds.

Keywords: Fuzzy Logic; Goldfish; pH water; Turbidity; Water Pump.

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1. Introduction

Keeping fish is one of the hobbies of most people, one of which is keeping goldfish. Goldfish are known as one of the ornamental fish that possess beauty and unique characteristics. According to data held by the Ministry of Maritime Affairs and Fisheries of the Republic of Indonesia, the freshwater ornamental fish sector contributes significantly to the Indonesian economy. Freshwater ornamental fish exports will be USD 111 million by 2020. Furthermore, the ornamental fish farming business can be considered one of the most cost-effective. This is inversely related to market conditions that drive the freshwater ornamental fish sector's strong demand. However, cultivators continue to face challenges such as the difficulty of performing regular coaching and supervising all of the monastery sites, which are many [1].

One of the common problems encountered when keeping fish in an aquarium is water quality. Non-tuberculous mycobacteria (NTM) are important diseases in wild, captive, marine, and freshwater fish, posing an infection risk to both aquarium fish and people. This study looked at the prevalence of NTM in ornamental fish from Ilam, western Iran. A total of 50 contaminated fish samples were collected and processed, with sediments added to Lowenstein-Jensen and Herrold egg medium. Positive colonies were assessed for growth rate, pigmentation, colony morphology, and biochemical activity, and molecular identification was accomplished using heat shock protein 65 kD gene (hsp65) sequencing. NTM were detected in 13 samples (26%), with 6 (46.2%) rapid-growing

strains and 7 (53.8%) slow-growing strains. Mycobacterium marinum was the most usually isolated species, posing a concern to both fish and people. The results emphasize ornamental fish as an important source of NTM[2]. Poor water quality can negatively impact the health and growth of goldfish, and can even lead to death. In an effort to maintain aquarium water quality, managing parameters such as water pH and turbidity levels is crucial for ensuring the well-being of goldfish. The pH level required for goldfish aquarium water is in the range of 7 – 8 [3], but many goldfish keepers do not pay attention to the pH level, resulting in suboptimal fish growth and even death.

To determine the pH level in a goldfish aquarium is something that ornamental fish keepers do not think about. Aquarium keepers must manually check the water's pH level using a pH meter. In addition, water turbidity also greatly affects the decline in the health of goldfish. If the water in the aquarium has become cloudy, the owner should start changing the water to keep the goldfish healthy. However, if the water does not appear cloudy but the pH level is below the parameter, there is no need to change the water; it is sufficient to raise the pH level in the aquarium[4].

In a Closed-Loop System, the use of feedback from sensors can optimize the dynamic measurement and correction of motor performance according to actual conditions[5]. By using sensors such as encoders, closed-loop control can continuously monitor parameters such as speed, torque, and motor position to quickly respond to changes in load or operational conditions[6]. This ensures that the motor operates according to the desired setpoint, improving precision and performance stability, whereas in an open loop system, commands are given without considering direct feedback from the system's conditions.

In this work, the author proposed to create a water quality control system for goldfish aquariums using fuzzy logic. The open-loop system responds to commands that have been predetermined, without the ability to adjust its operations according to changes in load or working conditions. The open-loop system tends to be less responsive and less able to respond to unexpected changes in the operational environment.

2. Materials and Methods

In this research, a system is needed that can maintain the quality of pH levels and water clarity in a goldfish aquarium. Thus, this system uses a water pump controlled by a fuzzy logic controller to drain and fill the water as needed. Since goldfish aquariums rarely experience acidic conditions (pH < 6.5), the control focus in this system is limited to pH > 9. However, two-way control will be a part of future developments. The mechanical specifications for this aquarium include dimensions of 40 x 20 x 30 cm made of acrylic glass. Meanwhile, the electronic specifications include a 220 VAC power supply, ESP32 processor, OLED display, output voltage of 0 – 12 VDC, and output current up to 60 A, as illustrated in Figure 1.

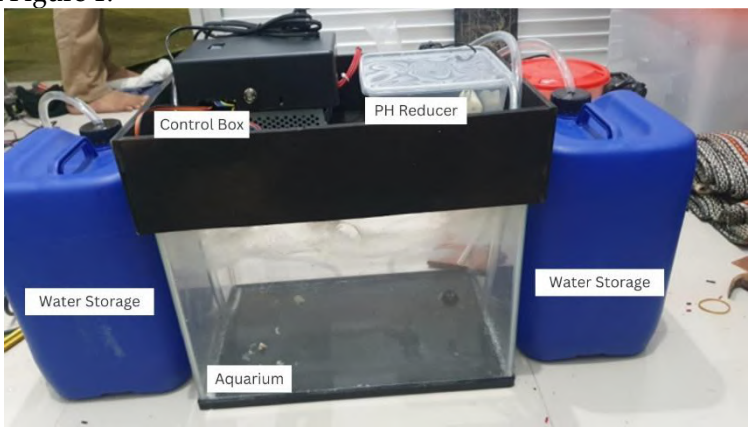

Figure 1. Water Quality Control System in Goldfish Aquarium Design.

2.1 Research Diagram

The purpose of a block diagram is to make it easier to depict the workflow of the system that will be constructed. The input to the general requirements of the intended system operation is where this procedure begins. The block diagram is made up of various parts. The system's block diagram, which includes input devices, processes, and outputs, is shown below. Murky water is drained by Pump 1 (DC 12V Pump 1), clean water is filled by Pump 2 (DC 12V Pump 2), and pH is neutralized by Pump 3 (micro pump).

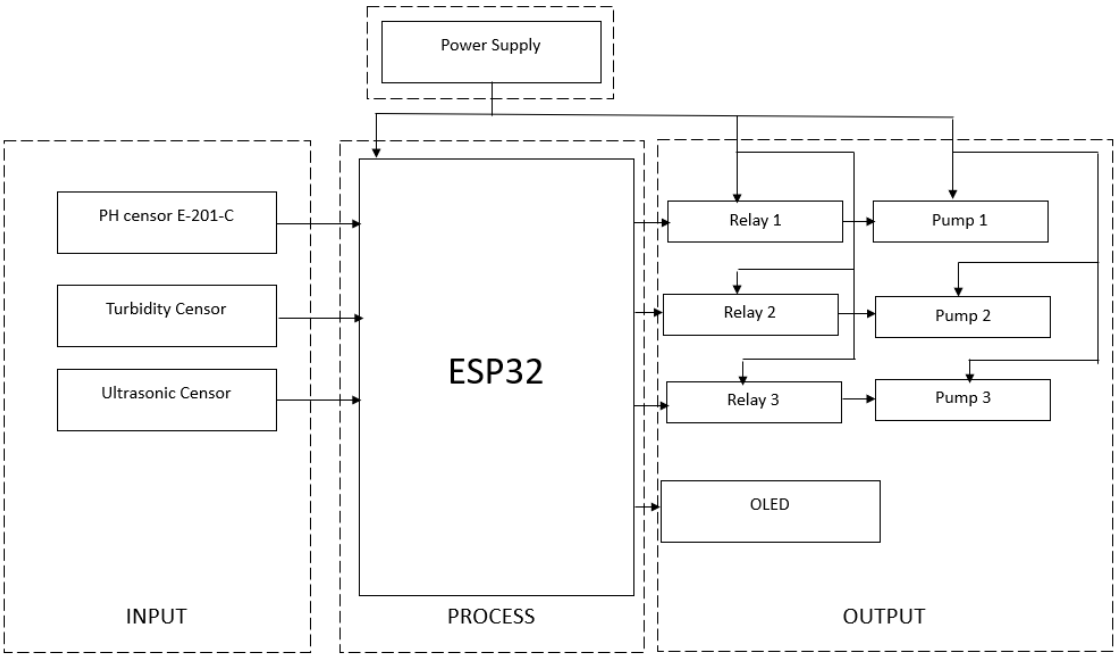

Figure 2. Block Diagram

2.2 Software Design

In Figure 2, there are fuzzy membership variables that will be used. The use of Fuzzy Logic in this tool is only as a pH controller for the goldfish aquarium using the mamdani method. The design of the Fuzzy logic in the system uses membership functions for water pH and turbidity. For acidic, neutral, basic categories on the pH scale are determined based on aquarium water quality standards. and clear water in aquarium terms generally has turbidity below 50 NTU. Water with turbidity above 100 NTU can stress sensitive tropical fish according to Encyclopedia of Aquarium Fish by Axelrod, H. R[7]

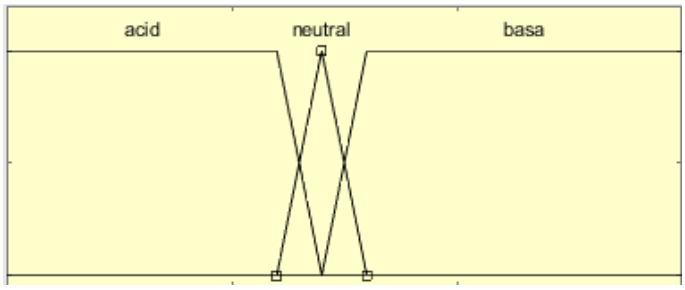

Figure 3. Fuzzy Membership Variables of Water pH

$$Acid = \begin{cases} 1\ ;\ x\ \leq 6 \\ \dfrac{(7-x)}{(7-6)}; 6\ <x\ <7 \\ 0\ ;\ x\ \geq 7 \end{cases}$$

$$Neutral = \begin{cases} 0\ ;\ x\ \leq 6\ atau\ c\ \geq 8 \\ \dfrac{(x-6)}{(7-6)}; 6\ <x\ <7 \\ \dfrac{(8-x)}{(8-7)}\ ;\ x\ \geq 7 \end{cases}$$

$$Basa = \begin{cases} 1\ ;\ x\ \geq 8 \\ \dfrac{(8-x)}{(8-7)}; 7\ <x\ <8 \\ 0\ ;\ x\ \leq 7 \end{cases}$$

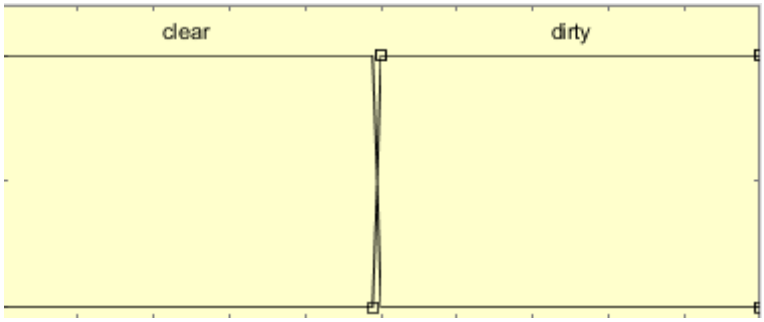

Figure 4. Fuzzy Membership Variables of Turbidity.

$$clear = \begin{cases} 1\ ;\ x\ \leq 49 \\ \dfrac{(49-x)}{(50-49)}; 49\ <x\ <50 \\ 0\ ;\ x\ \geq 7 \end{cases}$$

$$dirty = \begin{cases} 1\ ;\ x\ \geq 49 \\ \dfrac{(x-49)}{(50-49)}; 49\ <x\ <50 \\ 0\ ;\ x\ \leq 50 \end{cases}$$

After setting the fuzzy variable parameters for pH and water turbidity, the next step is to set the output membership variable parameters and provide the rulebase for the fuzzy system.

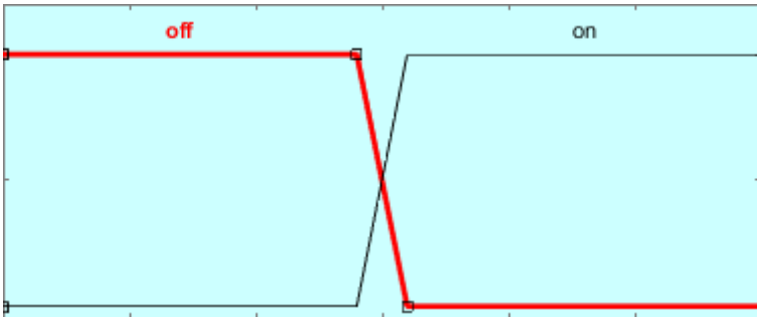

Figure 5. Output Membership Variables in Fuzzy

$$off = \begin{cases} 1\ ;\ x\ \leq 14 \\ \dfrac{(15-x)}{(15-14)}; 14\ <x\ <15 \\ 0\ ;\ x\ \geq 15 \end{cases}$$

$$on = \begin{cases} 1\ ;\ x\ \geq 15 \\ \dfrac{(16-x)}{(16-15)}; 15\ <x\ <16 \\ 0\ ;\ x\ \leq 15 \end{cases}$$

Next, add the rulebase using the "IF-THEN" rule that produces the following results:

1. If (pH is acidic) and (turbidity is clear) then (pump1 is off) (pump3 is off)
2. If (pH is acidic) and (turbidity is dirty) then (pump1 is on) (pump3 is off)
3. If (pH is neutral) and (turbidity is clear) then (pump1 is off) (pump3 is off)
4. If (pH is neutral) and (turbidity is dirty) then (pump1 is on) (pump3 is off)
5. If (pH is basic) and (turbidity is clear) then (pump1 is off) (pump3 is on)
6. If (pH is basic) and (turbidity is dirty) then (pump1 is on) (pump3 is on)

This reasoning is based on the fact that turbid water and high pH levels require both water replacement and pH neutralization. With the Mamdani method, using two inputs and two outputs. Then what will be obtained are six rules in the designed fuzzy system.

3. Experiments and Results

3.1 pH System Testing

pH system test aims to ensure that the water quality control system in the goldfish aquarium can operate optimally. In this test, a water quality control system with fuzzy control is used. The testing steps include the preparation of the necessary equipment, followed by testing the overall pH level of the water in the aquarium, and concluding with observation and recording of the test results to assess the overall performance of the system. A thorough system test was conducted to determine whether the pH control system in the goldfish aquarium is functioning properly, with the test results shown in the table 1.

Table 1. Testing the System Response Without Fuzzy Control

Time (Minute)	pH censor	Pump 3 (pH reducer)
00.00	10.70	Active
03.00	9.96	Active
05.00	7.64	Inactive
05.00	7.25(Neutral)	Inactive
08.00	9.20	Active
10.30	12.67	Active
11.02	14.58	Active
12.19	10.53	Active

Time (Minute)	pH censor	Pump 3 (pH reducer)
13.10	8.45	Active
13.30	7.24(Neutral)	Inactive
14.09	9.10	Active
14.50	11.75	Active
15.10	12.25	Active
17.08	10.03	Active
18.24	8.89	Active
20.10	6.82	Inactive
21.15	7.92	Inactive
23.57	9.77	Active
24.50	10.71	Active
26.01	11.84	Active
27.05	10.11	Active
29.07	7.10(Neutral)	Inactive
30.55	8.96	Active
31.49	9.74	Active
32.50	10.72	Active
33.10	11.85	Active
34.06	10.36	Active
36.57	7.97(Neutral)	Inactive

Based on the results of testing the system without controlling the aquarium's water quality, specifically pH, and using baking soda to boost the pH, which produced real-time data, it can be said that the pH levels' decline indicates variations. This happens because the micro pump's fluid production is controlled by an on-off mechanism rather than being precisely controlled, making it impossible to precisely adjust the volume of fluid delivered to lower the aquarium's pH.

Table 2. Results of System Response Testing to High pH Disturbances.

Time (Minute)	pH censor	Pump 3 (pH reducer)	Fuzzy
00.00	6.50	Inactive	7.68
02.55	7.10	Inactive	8.95
03.27	7.90	Inactive	21.1
05.01	9.20	Active	22.6
07.20	12.67	Active	22.6
09.30	14.58	Active	22.6
11.12	10.53	Active	22.6
12.15	8.45	Active	22.6
13.16	7.24(Neutral)	Inactive	11.1
14.09	9.10	Active	22.6
15.13	11.75	Active	22.6
15.58	12.25	Active	22.6
15.10	10.03	Active	22.6
16.07	8.89	Active	22.6
18.21	6.82	Inactive	7.52
20.11	7.92	Inactive	21.4
21.19	9.77	Active	22.6
23.43	10.71	Active	22.6
24.39	11.84	Active	22.6
26.01	10.11	Active	22.6
27.25	8.86	Active	22.6
28.30	7.10(Neutral)	Inactive	8.95
29.34	8.96	Active	22.6
30.25	9.74	Active	22.6
31.49	10.72	Active	22.6

Time (Minute)	pH censor	Pump 3 (pH reducer)	Fuzzy
32.47	11.85	Active	22.6
33.18	10.36	Active	22.6
34.25	9.24	Active	22.6
36.38	7.97	Inactive	21.1

Table 2 describe the experiment testing the system's response to disturbances in the form of pH levels higher than the setpoint. It takes approximately 8 minutes for the water's pH to return to the setpoint marked with an orange color table.

3.2 Overall Water Turbidity Testing

This test aims to assess whether the water quality control system in the goldfish aquarium is functioning optimally. The tool used in this test is the goldfish water quality control system. The procedure of the test includes equipment preparation, the complete execution of the test on the turbidity level of the aquarium water, as well as observation and recording of the overall system test results. With the test results, they can be seen in the table 3:

Table 3. Water Turbidity System Testing

NTU	Pump 1 (Discharging Water)	Pump 2 (Adding Water)	Ultrasonic sensor	Fuzzy
100	Active	Inactive	10	22.8
80	Active	Inactive	12	22.8
60	Active	Inactive	14	22.8
40	Active	Inactive	16	7.68
20	Active	Inactive	18	7.68
10	Active	Inactive	19	7.68
0	Inactive	Active	20	7.68
0	Inactive	Active	18	7.68
0	Inactive	Active	16	7.68
0	Inactive	Active	14	7.68
0	Inactive	Active	12	7.68
0	Inactive	Inactive	10	7.68

From the experiment, when the turbidity sensor detects water turbidity reaching more than 50 NTU, the system will automatically perform a drainage. The water drainage in this aquarium is carried out using a DC 12V 1 pump to remove the turbid water. This process will stop automatically when the ultrasonic sensor detects the water level reaching 20 cm, taking 5 minutes and 20 seconds. After that, the 12V DC pump 2 will turn on to fill with clean water, and will stop when the ultrasonic sensor detects a water height of 10 cm. At this point, the turbidity sensor will ensure that the water turbidity reaches 0 NTU, indicating that the water is clean. Filling the clean water takes 15 minutes and 24 seconds.

4. Conclusions

Based on the problem formulation, mechanical planning, and the design of the water quality control system in a goldfish aquarium with fuzzy control, several conclusions can be drawn. First, the water quality control system using the fuzzy method is capable of operating with a low error rate. Second, from the test results, this system can lower the water's pH level to the specified point. Third, the water turbidity control system will automatically drain the dirty water when the turbidity level reaches 50 NTU, with a drainage time of 5 minutes and 20 seconds using a 12V DC 1 pump. Finally, the pH and turbidity monitoring system is functioning well according to the readings on the OLED.

References

1. A. F. Nurzaman, M. Wildan, and N. Anisa, "Development of Internet of Things System for Smart Fishery in Ornamental Fish Farming," in *Proceedings of 2023 International Conference on Information Management and Technology, ICIMTech 2023*, 2023. doi: 10.1109/ICIMTech59029.2023.10277831.
2. M. Yazdanmanesh, K. Tadayon, D. Bagherian Koshkghazi, and N. Mosavari, "Isolation and identification of non-tuberculous mycobacteria from aquarium fish in Ilam, Iran," *J. Clin. Tuberc. Other Mycobact. Dis.*, vol. 37, 2024, doi: 10.1016/j.jctube.2024.100478.
3. M. Cleal, A. Gibbon, B. D. Fontana, and M. O. Parker, "The importance of pH: How aquarium water is affecting behavioural responses to drug exposure in larval zebrafish," *Pharmacol. Biochem. Behav.*, vol. 199, 2020, doi: 10.1016/j.pbb.2020.173066.
4. K. L. Onthank *et al.*, "The Open acidification Tank Controller: An open-source device for the control of pH and temperature in ocean acidification experiments," *HardwareX*, vol. 14, 2023, doi: 10.1016/j.ohx.2023.e00435.
5. N. L. Manuel, N. İnanç, and M. Lüy, "Control and performance analyses of a DC motor using optimized PIDs and fuzzy logic controller," *Results Control Optim.*, vol. 13, 2023, doi: 10.1016/j.rico.2023.100306.
6. L. Zhang, "A Deployment and Coverage Optimization Algorithm for Self-Powered Wireless Sensor Networks Based on Hybrid Swarm Intelligence," *IEEE Sens. J.*, vol. 23, no. 18, 2023, doi: 10.1109/JSEN.2022.3230955.
7. H. R. Axelrod, *Encyclopedia of Aquarium Fish*. Neptune City, New Jersey: TFH Publications, 2005.