Journal of Experimental and Applied Physics
Journal Homepage: jeap.ppj.unp.ac.id
Vol. 2, No. 3, September 2024.
ISSN (Print): 2988-0378 ISSN (Online): 2987-9256

Preliminary Results: Design Of Servo-Controlled Titrant Flux Regulation System

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Article History
Received : Dec, 16th 2024
Revised : Dec, 25th 2024
Accepted : Dec, 31st 2024
Published : Dec, 31st 2024

DOI:
https://doi.org/10.24036/jeap.v2i3.82

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Abstract: Automation in laboratory instruments has transformed chemical analysis by enhancing precision and efficiency. Despite these advancements, inconsistent control of titrant flow remains a significant challenge in titration processes, often affecting the accuracy of results. This study introduces a novel titrant flow regulation system utilizing a servo motor and the PCA9685 driver to address this issue. The research involves simulation, prototyping, and performance testing to ensure optimal reliability and accuracy. The system is engineered to precisely regulate titrant flow, overcoming the limitations of traditional manual or semi-automated titration techniques. Experimental results demonstrate that the proposed system achieves an average titrant flow accuracy of 97.34%, with a minimal mean error rate of 2.65%. These findings highlight the effectiveness of the servo motor-based approach in maintaining consistent flow rates, even in complex titration scenarios. The proposed system is not only cost-effective but also easily adaptable for integration into various laboratory environments, paving the way for more reliable and efficient automated titration processes. With its significant potential for improving accuracy and reproducibility, this innovation represents a critical step forward in the development of modern analytical chemistry techniques.

Keywords: Automated Titrator, Flux Regulation, PCA9685, Servo Motor, and Titrant.

1. Introduction

Titration is a common laboratory method in analytical chemistry used to determine the concentration of a substance in a sample [1]. This method involves the gradual addition of a titrant to a known volume of the sample until the reaction reaches a measurable endpoint, such as a color change or pH shift. While conventional titration methods are effective, they often require manual intervention, making them time-consuming and susceptible to human error [2]. In recent years, there has been a significant push towards automating laboratory processes to enhance precision, efficiency, and repeatability [3]. Automated titration systems have emerged as a solution, integrating various sensors, controllers, and actuators to perform titrations with minimal human intervention [4]. Among these advancements, the design of a servo-controlled titrant flux regulation system represents a cutting-edge approach, promising finer control over titrant delivery, thereby improving the accuracy and consistency of titrations.

However, developing such a system presents several challenges [5]. Achieving precise control over the titrant flow rate is critical, as variations can lead to inaccuracies in endpoint detection, affecting the overall reliability of the titration process [6]. System integration is another significant challenge, requiring effective communication and accurate real-time response between sensors, actuators, and controllers [7]. Additionally, the cost and accessibility of developing an automated titration system that is both affordable and available to a wide range of laboratories, including those with limited resources [8]. Balancing cost with functionality without compromising performance is essential [9, 10]. User interface and usability are also important considerations; the system must be user-friendly to ensure easy operation by laboratory technicians [11]. Moreover, regular maintenance and calibration are necessary to ensure long-term accuracy and reliability, so designing a system that facilitates easy maintenance and calibration procedures is vital for sustained performance [12, 13].

The push towards automation in laboratory settings is driven by the need for higher throughput, accuracy, and reproducibility of results [14, 15]. Automated titration systems are increasingly relevant in various industries, including pharmaceuticals, environmental testing, food and beverage quality control, and chemical manufacturing [16]. These systems reduce the labor intensity of routine analyses and minimize the potential for human error, leading to more reliable data [17]. A servo-controlled titrant flux regulation system offers enhanced precision in titrant delivery, which is particularly beneficial in applications requiring high accuracy, such as the determination of trace amounts of analytes in complex matrices [18]. Furthermore, as industries move towards stricter regulatory standards, the demand for reliable and automated analytical techniques is expected to rise [19].

Previous research has utilized peristaltic pumps to analyze acid-base titrations, achieving measurement precision down to milliliters. This method aimed to improve the accuracy and efficiency of titration processes. However, the study encountered significant limitations. One major issue was the accuracy of the titrant volume delivered by the peristaltic pump, which resulted in a high percent error. This inaccuracy could potentially affect the reliability of the titration results, highlighting the need for improvements in the precision of volume delivery mechanisms [20].

In another study, peristaltic pumps were employed to measure the volume of solutions in liters. While this method was effective for handling larger volumes, it faced its own set of limitations. Specifically, the research was constrained to measurements in liters, without the capability to measure smaller volumes accurately. This lack of versatility limited the applicability of the findings, particularly in experiments requiring precise measurements of smaller quantities of solution [21]. These studies underscore the need for more advanced titration methods that can offer both high accuracy and the flexibility to handle a wide range of volumes, from milliliters to liters. Improving the precision of titrant delivery and expanding the measurable volume range are critical for enhancing the reliability and applicability of titration techniques in various scientific and industrial contexts.

2. Materials and Method

This research falls under the category of engineering studies. Its primary objective is to develop a flux regulator system for an automatic titrator, aimed at facilitating laboratory research. In this study, design and construction methods are employed, focusing on the tools and components used within the system [22]. The engineering design of the flux regulator is expected to offer improved functionality over previous systems.. The goal is to create a more efficient and reliable titration process, enhancing the accuracy and ease of use in laboratory settings.

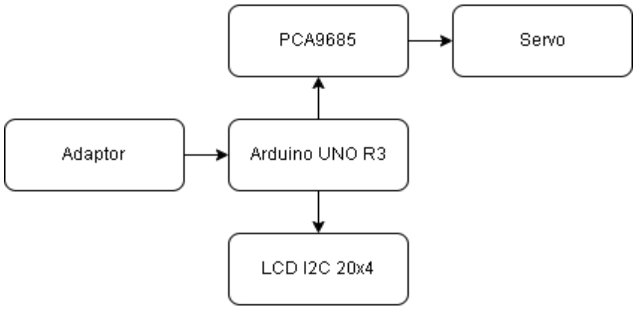

Figure 1. Flux regulator system block diagram

Based on Figure 1, the flux regulator system incorporates several critical components: the PCA9685 servo driver, a microcontroller, a display, and a servo motor. The PCA9685 servo driver plays a pivotal role in ensuring the stability of the data transmitted to the servo, thereby enhancing its operational efficiency. The servo motor employed within this system is the MG996R, selected for its reliability and performance. The central processing unit of the flux regulator system is the Arduino Uno R3 microcontroller, which serves as the primary control unit, orchestrating the system's operations. Power for the entire system is provisioned through a 5-volt, 2-ampere adapter, which supplies both the Arduino and the PCA9685 driver, ensuring a stable power supply crucial for consistent performance. This design aims to enhance the precision and reliability of flux regulation in laboratory settings, addressing the need for stable and accurate control in experimental procedures.

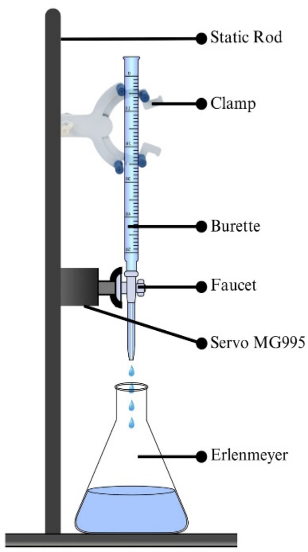

Figure 2. Ilustration flux regulator system block diagram [23]

Several components are integrated into the system, forming an interconnected arrangement to achieve the desired outcomes. The system incorporates a burette to hold the titrant solution, with the burette valve connected to a servo motor to precisely control the dispensed volume of the titrant. The hardware design illustration can be seen in Figure 2. In this setup, the servo motor is crucial for regulating the volume of titrant released, ensuring accurate and repeatable titrations. This configuration exemplifies the synergy between hardware components and control software, resulting in a reliable flux regulation system tailored for laboratory use [24]. The precise control over titrant volume, facilitated by the servo motor and driver, enhances the accuracy of titration processes, making this system a valuable tool for scientific research and experimentation.

The core functionality of the system revolves around accurately measuring and controlling the volume of titrant dispensed from the burette. The Arduino UNO R3 microcontroller, programmed via the Arduino IDE, serves as the central control unit, managing inputs from the servo motor and calculating the volume based on the time and angle of servo movement. The detailed process of this programming is illustrated in the flowchart shown in Figure 3.

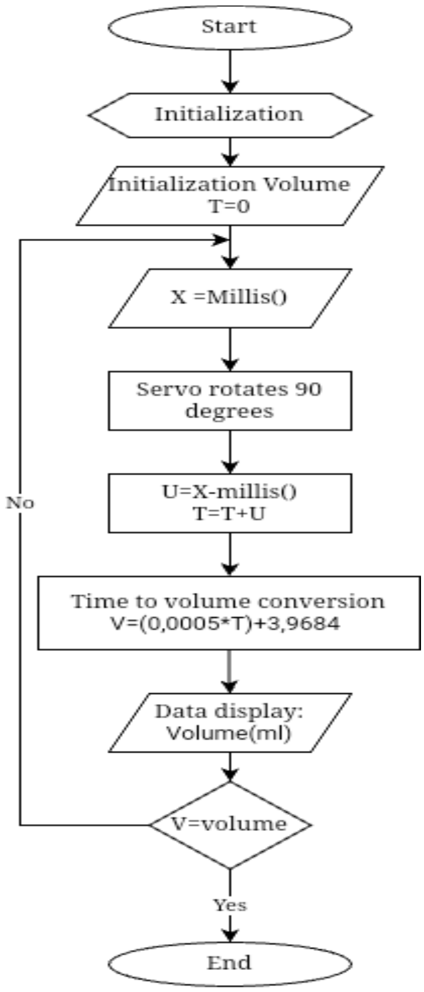

Figure 3. Flowchart System

Based on the flowchart, the system begins with the initialization of the equipment, followed by the input of the desired volume. The system then calculates the time required for the servo to rotate 90 degrees, which is crucial for determining the corresponding volume. This time is then processed using a specific equation to convert it into a volume value. The program subsequently analyzes whether the initially inputted volume matches the final volume after the flux regulator has completed its process. If the volumes do not align, the system automatically adjusts by rotating the servo 90 degrees again until the final volume accurately matches the desired input. This automated feedback loop ensures precise volume control, enhancing the system's accuracy and reliability, making it a valuable tool for applications requiring meticulous fluid measurement.

3. Results and Discussion

The results of the research were obtained from the characterization of the system using a servo. The arrangement and integration of these components were essential in achieving the desired performance and functionality of the system. The servo plays a crucial role in this setup, enabling precise control and operation, which is vital for the system's overall accuracy and reliability [25]. This system operates with an input voltage supplied by a 5-volt, 2-ampere adapter, which powers all the device components. The actuator mechanism uses an MG996R servo motor to control the burette valve. This servo motor has three pins: VCC, GND, and data to ensure stable PWM signals and optimal data readings. The servo is controlled using the PCA9685 driver connected to four pins: VCC, GND, SDA, and SCL.

The characterization measurement data was obtained by comparing time and volume from the burette. In this study, the millis function in Arduino IDE was used to measure time. To derive the equation, a linear correlation was performed on the data to determine the regression coefficient, using the relationship between time and volume from the burette, as illustrated in Figure 4. The regression coefficient obtained from the linear correlation is 1. The correlation formula between time and volume is expressed in the following equation (1).

$$V = (0{,}0005 \cdot T) + 3{,}9684 \quad (1)$$

In this context, V represents the volume measured by the equipment, and T denotes the time value obtained from the Arduino millis() function. The volume was measured by varying the data using 10 different measurements, resulting in a linear equation as shown in Figure 4. The use of linear regression to fit the data provides a reliable mathematical framework for describing the system's performance [26]. This approach not only validates the system design but also highlights its potential applications in various laboratory settings [27].

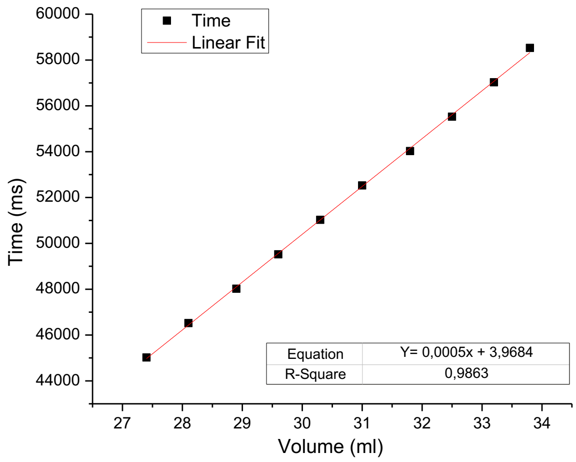

Figure 4. Graph of the Relationship between Time and Volume

Figure 4 presents the characterization test graph. According to this graph, time is directly proportional to volume. This relationship indicates that the measurements for the volume parameter are highly reliable. The R-squared value obtained from the linear is 0.9863. This high R-squared value signifies that the linear model accurately represents the data, confirming the system's precision in measuring [28] and controlling the titrant volume. The direct proportionality observed in the graph further reinforces the overall effectiveness of the system. These results validate the performance of the flow regulation system in maintaining accurate volume measurements, which is crucial for ensuring the reliability and accuracy of laboratory experiments and research applications. The data presented in Table 1 illustrate the accuracy of the flow regulator, highlighting its performance in maintaining precise control over fluid flow.

Table 1. Measurement Accuracy

Measurement Order	Burret (ml)	Flux Regulation (ml)	%Error	%Accuracy
1	27,4	26,48	3,36	96,64
2	28,1	27,22	3,1	96,9
3	28,9	27,98	3,19	96,81
4	29,6	28,73	2,94	97,06
5	30,3	29,48	2,7	97,3
6	31	30,23	2,48	97,52
7	31,8	30,98	2,58	97,42
8	32,5	31,73	2,37	97,63
9	33,2	32,48	2,16	97,84
10	33,8	33,23	1,68	98,32
	Average		2,65	97,34

This level of accuracy highlights the system's capability to provide reliable and consistent volume measurements, which are essential for accurate titration in laboratory settings [29]. Ensuring such a high degree of accuracy is crucial for achieving dependable results in experiments and research that depend on precise volumetric analysis [30]. The data in Table 2, analysis reveals that the percentage error ranges from 0.48% to 7%, with the highest error observed in the first measurement (7%) and the lowest in the second (0.48%). Correspondingly, the percentage accuracy varies between 93% and 99.52%, indicating that the system stabilizes and performs more reliably with larger volumes. A notable trend is that as the volume of the titrant increases, the error decreases, suggesting that the system operates with greater precision at higher volumes. The average percentage error across all measurements is 2.42%, while the average accuracy is 97.58%, demonstrating that the system is generally reliable and precise in delivering the titrant. This high level of accuracy, especially in larger volumes, indicates that the system is well-suited for automated titration processes, where precise control of titrant flow is critical. Overall, the system exhibits robust performance, with the initial higher error likely due to calibration needs, but quickly stabilizing to deliver accurate results.

Table 2. Precision of Measurement

Measurement Order	Flux Regulation (ml)	Burret (ml)	%Precision
1	19,8	19,2	96,88
2	18,4	19,2	95,83
3	18,5	19,2	96,35
4	18,7	19,2	97,4
5	17,7	19,2	92,19
6	19,3	19,2	99,48
7	18,8	19,2	97,92
8	18,8	19,2	97,92
9	19,2	19,2	100
10	20	19,2	95,83
Average	18,92	19,2	96,98
SD	0,68		
RSD	3,60		

Achieving high precision in data measurement is crucial to ensuring the reliability and repeatability of the titration process [31]. This level of precision demonstrates that the system can consistently deliver accurate data with minimal deviation, which is essential for maintaining the integrity of experimental results [32]. Precise data highlights the robustness of the system and its suitability for applications requiring strict volume control [33]. The data analysis in Table 2 reveals that the titrant flow regulation system exhibits high precision and consistency across various measurements, with most flow rate values closely matching the target burette volume of 19.2 ml. The precision percentage is predominantly 97%, with minor deviations, including one instance of maximum precision at 100% and another slightly lower at 92.19%. The system's average flow rate setting is 18.92 ml, maintaining an average precision of 96.98%, which demonstrates its reliability in delivering titrant volumes close to the desired target. A standard deviation of 0.68 and a relative standard deviation of 3.6% indicate minimal variability, underscoring the system's consistency and accuracy.

Based on data analysis, it can be concluded that this research has developed a more advanced titration method. This method offers high accuracy and flexibility in handling measurements across a wide range of volumes, from milliliters to liters. Enhancing the precision of titrant volume measurements and expanding the measurable volume range is crucial for improving the reliability and application of titration techniques in various scientific and industrial contexts through the characterization of servo motors. The characterization results of titrant volume using the servo motor demonstrate good accuracy and precision with minimal errors in titrant volume control.

4. Conclusion

This study successfully designed and developed a titrant flow control system powered by a servo motor, aimed at enhancing accuracy and consistency in the titration process. The results demonstrated an average titrant flow accuracy of 97.34%, with a minimal average error rate of only 2.65%. The system exhibited a strong linear relationship between time and volume, with a high correlation coefficient (R-squared) of 0.9863, indicating its capability to regulate titrant flow with exceptional precision. These findings address the critical challenge of inconsistent titrant flow control, thereby improving the reliability of analytical results. By leveraging the PCA9685 driver and MG996R servo motor, the system ensures precise control over the dispensed titrant volume, significantly reducing human error and enhancing laboratory testing efficiency. The results highlight the system's cost-effectiveness, adaptability, and superior performance across diverse laboratory settings. This innovation represents a transformative solution for modern analytical techniques, offering improved accuracy and reproducibility while paving the way for more reliable and efficient automated titration processes. With its broad application potential, the system marks a significant advancement in laboratory automation and chemical analysis, providing a robust and scalable approach to meet the evolving needs of modern laboratories.

Acknowledgments

The author would like to express their sincere gratitude to the Department of Physics, especially the Electronics and Instrumentation Laboratory, Universitas Negeri Padang, for the support in the form of research facilities that greatly assisted in the smooth data collection process.

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