

Design of a Servo-Controlled Variable Resistor

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ABSTRACT

This study develops an innovative servo-controlled variable resistor to address the need for precise programmable resistance in modern electronics. While manual potentiometers lack automation capability and digital versions introduce quantization errors, the proposed hybrid solution combines microcontroller-driven servo mechanisms with standard rotary potentiometers, preserving analog quality with digital control. Through experimental methodology involving system design, hardware implementation, and software development, the author created and tested an electronically adjustable resistor system. Rigorous evaluation across 738 trials demonstrated exceptional performance: average standard deviation of 0.009, data range of 0.07, and coefficient of variation (CV) of 0.564%, approaching Six Sigma precision (3.4 defects per million). Statistical analysis confirmed the system's stability and repeatability, outperforming both manual adjustment (typical CV >5%) and digital alternatives. The results establish our servo-controlled design as a superior solution, offering precise programmability without compromising analog signal integrity. This advancement enables new applications in automated testing, and adaptive circuits where traditional variable resistors prove inadequate. The research contributes a reliable control mechanism for analog components while setting quantitative benchmarks for programmable resistance systems.

Keywords: Servo, rheostat, microprocessor, resistor, variable.

ABSTRAK

Penelitian ini mengembangkan resistor variabel terkontrol servo yang inovatif untuk memenuhi kebutuhan resistansi yang dapat diprogram secara presisi dalam elektronik modern. Sementara potensiometer manual tidak memiliki kemampuan otomatisasi dan versi digital menimbulkan kesalahan kuantisasi, solusi hibrida yang diusulkan menggabungkan mekanisme servo berbasis mikrokontroler dengan potensiometer rotary standar, mempertahankan kualitas analog dengan kendali digital. Melalui metodologi eksperimen yang melibatkan desain sistem, implementasi perangkat keras, dan pengembangan perangkat lunak, penulis menciptakan dan menguji sistem resistor yang dapat disesuaikan secara elektronik. Evaluasi ketat pada 738 percobaan menunjukkan kinerja luar biasa: deviasi standar rata-rata 0,009, rentang data 0,07, dan koefisien variasi (CV) 0,564%, mendekati presisi Six Sigma (3,4 cacat per juta). Analisis statistik mengkonfirmasi stabilitas dan keterulangan sistem, mengungguli kedua metode penyetelan manual (CV tipikal >5%) dan alternatif digital. Hasil penelitian menetapkan desain terkontrol servo ini sebagai solusi superior yang menawarkan kemampuan pemrograman presisi tanpa mengorbankan integritas sinyal analog. Kemajuan ini memungkinkan aplikasi baru dalam pengujian otomatis dan rangkaian adaptif di mana resistor variabel tradisional terbukti tidak memadai. Penelitian ini memberikan mekanisme kendali yang andal untuk komponen analog sekaligus menetapkan tolok ukur kuantitatif untuk sistem resistansi yang dapat diprogram.

Kata Kunci: Servo, rheostat, mikroprosesor, resistor, variabel.

I. INTRODUCTION

The evolution of modern electronic and automation systems has created an imperative need for precise and programmable control of analog parameters [1-3]. Among these critical parameters, resistance plays a pivotal role in circuit design, affecting voltage division, current regulation, and signal conditioning across diverse applications from industrial controls to precision instrumentation [4-5]. Conventional implementations relying on manual adjustment of variable resistors or potentiometers [6-8] present

fundamental limitations in today's increasingly automated and remote-controlled environments, creating a significant technological gap in programmable analog control solutions.

Current alternatives such as digital potentiometers, while addressing programmability requirements, introduce their own limitations including quantization errors, limited bandwidth, and digital noise coupling [9-11]. This research proposes an innovative hybrid solution that bridges the analog-digital divide: a servo-mechanically controlled potentiometer system. By integrating a microcontroller-

driven servo actuator with standard rotary potentiometers, the author develop an electronically controlled variable resistor that maintains the signal integrity advantages of analog components while enabling precise digital programmability. This study aims to comprehensively design, implement, and validate a servo-controlled variable resistor system with three primary objectives: (1) to demonstrate the technical feasibility of the servo-potentiometer interface mechanism, (2) to quantify the system's performance metrics including accuracy (targeting $\sigma < 0.01$), repeatability ($CV < 1\%$), and (3) to establish its advantages over existing solutions through comparative analysis.

Through extensive experimental validation involving 738 measurement trials, the author demonstrate that this approach successfully combines the superior analog characteristics of mechanical potentiometers with the programmability of digital systems, while avoiding their respective limitations. The research contributes to the field by: (a) introducing a control mechanism for analog components, and (b) establishing performance benchmarks for hybrid programmable resistors.

II. METHOD

This study employs an experimental method to design, build, and test a servo-controlled variable resistor system. The methodology consists of several key stages: system design, hardware development, software programming, and experimental testing, as illustrated in Figure 1.

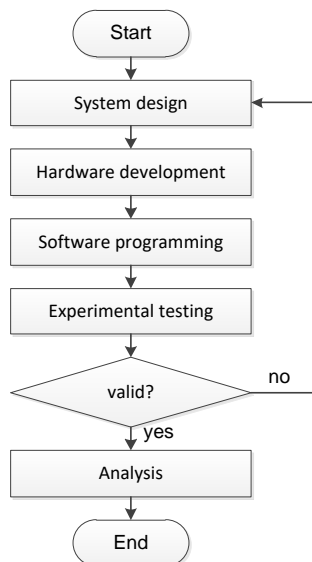


Figure 1. Methodology flowchart

A. System Design

The system is designed to allow electronic control of resistance using a servo motor to rotate a mechanical potentiometer. The main components of the system include rotary potentiometer 100 Ohm 100W, servo motor, microcontroller, power supply, and mechanical coupler.

B. Hardware Development

The potentiometer is mechanically coupled to the servo motor, allowing the servo shaft to rotate the potentiometer's knob. The entire assembly is mounted on a non-conductive board to ensure stability. Proper alignment between the servo and potentiometer is ensured to avoid mechanical stress or slippage. Figure 2 shows the schematic diagram of the

system. The power supply provides stable voltage to the entire circuit, ensuring consistent operation of the servo motors and microprocessor. The microprocessor serves as the central controller, processing input signals and dynamically adjusting the positions of Servo 1 and Servo 2, which are mechanically linked to Rheostat 1 and Rheostat 2, respectively. By rotating the servo arms, the system modifies the resistance values of the rheostats, enabling real-time tuning of electrical parameters. The input module allows external control signals or user-defined settings to influence the resistance adjustment process.

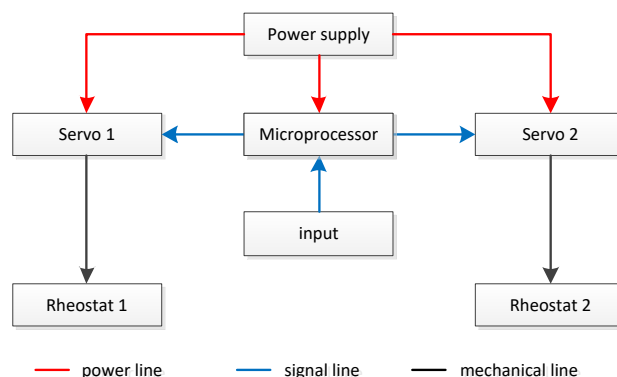


Figure 2. The schematic diagram of the proposed system

C. Software Programming

In this study, an ATmega328P microcontroller integrated on an Arduino Uno R3 development board is implemented. The microcontroller is programmed using Arduino IDE version 1.8.19 to control the rotation angle of the servo motor, thereby adjusting the resistance value of the potentiometer. Pulse Width Modulation (PWM) signals are employed for precise servo positioning. The system utilizes serial communication for both target angle input and output data monitoring. The control algorithm flowchart is presented in Figure 3.

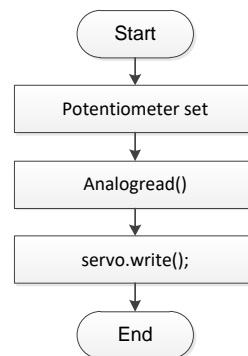


Figure 3. Code flowchart

D. Experimental Testing

The experiments aim to characterize the relationship between servo angle and resistance output while evaluating the system's accuracy, repeatability, and stability. Figure 4 presents the testing flowchart for the servo-controlled rheostat system. During testing, the rheostat is automatically measured at two key positions: 5° and 175° . These angles were strategically chosen based on the servo's $0-180^\circ$ operational range while avoiding mechanical limitations near the extremes. By offsetting the measurement points from the absolute limits, potential issues such as stalling, or excessive

mechanical stress are mitigated, ensuring more reliable data collection.

The selection of 5° and 175° as test points provides a representative evaluation of the rheostat's performance across nearly its full working range [12] while maintaining a safety margin for the servo mechanism. This approach not only safeguards the hardware from potential damage but also minimizes measurement errors that could arise from operating at the absolute limits of motion. The automated measurement process enhances consistency across repeated trials, enabling thorough analysis of the system's behavior under controlled conditions. Through this methodology, the experiments effectively assess the servo-rheostat system's precision and stability while accounting for real-world mechanical constraints.

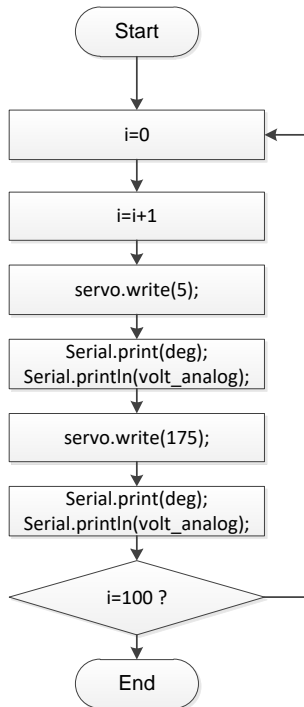


Figure 4. The experiment testing flowchart

Figure 5 illustrates an experimental setup designed to test the consistency of a servo-based rheostat system using analog input readings. The microprocessor serves as the central processing unit, while two rheostats (Rheostat 1 and Rheostat 2) are connected to provide variable resistance, simulating real-world adjustments. The system is powered by a 5 VDC supply, with a ground connection ensuring stable signal integrity. Instead of measuring resistance directly (which would require additional current sensors), the setup simplifies the process by reading voltage output, making it easier to evaluate the rheostats' performance under varying conditions.

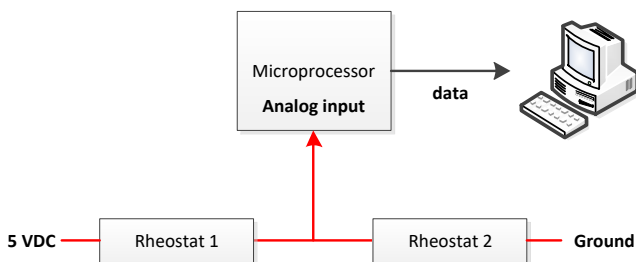


Figure 5. The schematic of hardware testing

The analog input plays a critical role in this test by converting the voltage fluctuations from the rheostats into digital data for the microprocessor to analyze. The rheostats, adjusted via servos, allow for precise control over resistance changes, enabling systematic testing of output consistency. By focusing on voltage readings rather than resistance, the system avoids the complexity of current measurement while still providing reliable data on the rheostats' behavior. This approach ensures efficient and repeatable testing, which is essential for validating the stability and accuracy of servo-controlled rheostat systems. This simplified yet effective configuration demonstrates a practical method for evaluating servo-based rheostat performance in embedded systems.

III. RESULTS AND DISCUSSION

E. Hardware And Software Design

The servo motor is mechanically coupled to the rheostat shaft, as shown in Figure 6. The integrated mounting system provides a shared base for both components, enabling precise servo-controlled rotation of the rheostat.



Figure 6. Proposed servo-controlled variable resistor (1) servo (2) mechanical coupling (3) 100 ohm 100 W rheostat (4) mounting

Figure 7 presents the hardware components used for evaluating and testing the proposed servo-actuated system. The digital multimeter monitors output electrical parameters, while the variable resistor serves for initial servo and rheostat setup to prevent prototype failure caused by mechanical limitations. This precaution is crucial because rheostats have rotation limits that must be considered during servo installation. An Arduino Uno R3 development board generates PWM signals for servo control. A stabilized 6V power supply provides adequate operating voltage for both the Arduino and servo motor.

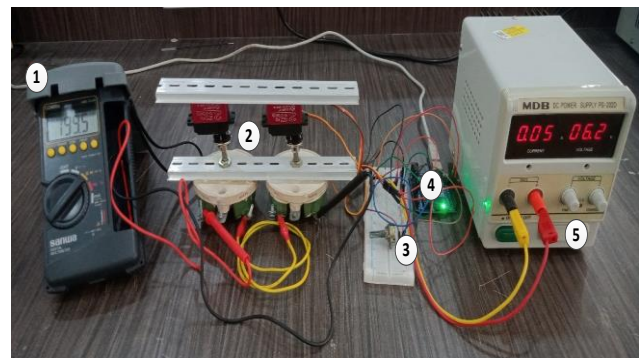


Figure 7. Prototype testing configuration (1) multimeter (2) proposed prototype (3) variable resistor (4) microcontroller (5) power supply

The prototype testing implementation employs a control algorithm developed in accordance with the flowchart presented in Figure 4, utilizing Arduino IDE version 1.8.19. The programmed control sequence implements a repetitive loop alternating between 5° and 175° servo positions, with a 1.5-second dwell time at each angular position.

F. Results and Discussion

Following hardware and software configuration, the system was executed for testing and evaluation. The Arduino Uno R3 development board acquired analog signals corresponding to the voltage across the rheostat, as illustrated in Figure 5. These signals were transmitted from the microprocessor to a computer via serial print commands and displayed on the Arduino IDE serial monitor. The digital data displayed on the serial monitor required conversion to analog voltage values using (1).

$$\text{rheostat voltage} = \text{digital data} / 1023 \times 5 \text{ volt} \quad (1)$$

The value of 1023 originates from the 10-bit ADC resolution integrated in the ATmega328P microcontroller, where 5 volts represents the maximum readable voltage threshold for the ADC. The converted voltage data were subsequently visualized and subjected to frequency distribution analysis, as presented in Figures 8 through 11.

Figure 7 presents voltage measurements from 369 experimental trials conducted with the servo mechanism fixed at 5°, demonstrating exceptional output stability in the servo-controlled rheostat system. The recorded voltages exhibit a remarkably tight distribution ranging from 3.83 V to 3.92 V, representing a total variation of just 0.09 V. This corresponds to a coefficient of variation (CV) of 0.21% (with a mean of 3.878 V and standard deviation of 0.008 V), indicating the system maintains >99% output consistency across all measurements.

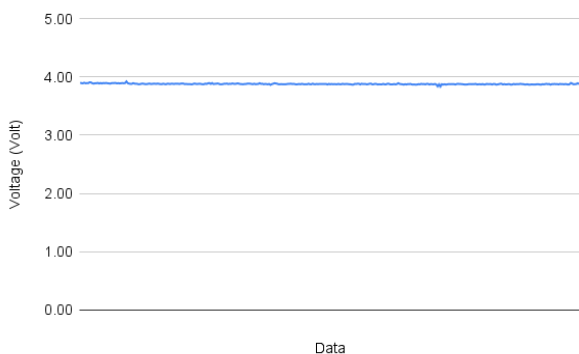


Figure 7. Voltage measurement results from at 5°

Figure 8 presents voltage measurements from 369 experimental trials at a fixed 175° servo position, confirming similarly excellent output stability in the servo-controlled rheostat system. The voltage distribution ranges narrowly from 1.16 V to 1.21 V ($\Delta=0.05$ V), with a mean of 1.176 V and standard deviation of 0.011 V. This yields a coefficient of variation (CV) of 0.94%, demonstrating comparable consistency (>99%) to the 5° position results (Figure 7), despite the different mechanical configuration.

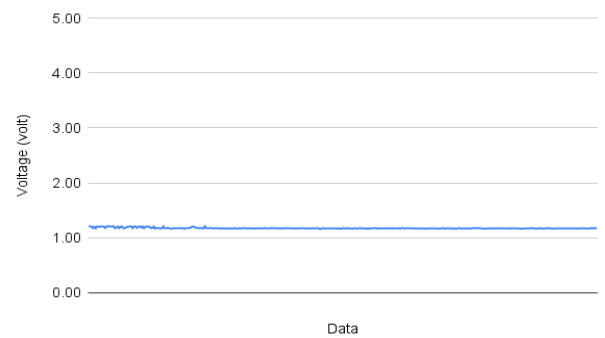


Figure 8. Voltage measurement results from at 175°

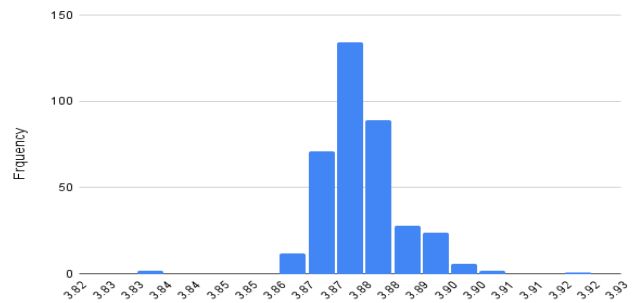


Figure 9. Frequency distribution of voltage measurements at 5°

Figure 9 displays the frequency distribution of voltage measurements from the servo-controlled rheostat system, providing further insight into the output stability previously analyzed in Figures 7. The histogram reveals a pronounced clustering of values around 3.87 – 3.88 V, with the highest frequency reaching 134 counts, indicating a strong central tendency. The voltage measurements span a narrow range from, highlighting the system's exceptional consistency.

When compared to earlier results, this distribution exhibits improved precision relative to the 5° position data (Figure 7, $\Delta=0.09$ V) and comparable stability to the 175° measurements (Figure 8, $\Delta=0.05$ V). The left-skewed pattern of the histogram suggests a potential systematic lower-bound effect, which may arise from minor servo hysteresis or contact resistance variations during rheostat operation. The dominant mode at 3.99 V underscores the system's capability for high-precision voltage regulation, making it particularly suitable for applications demanding sub-1% variation, such as reference voltage generation in metrology or sensor calibration. The observed asymmetry in the distribution warrants further investigation into mechanical tolerances and their impact on performance at this specific servo angle.

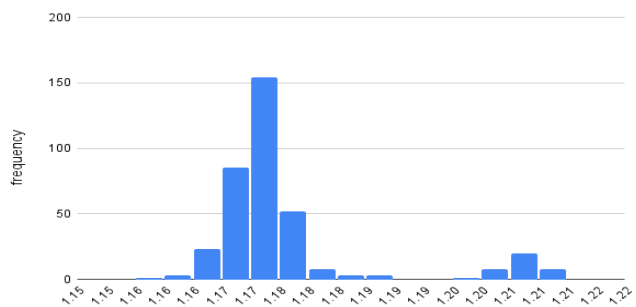


Figure 10. Frequency distribution of voltage measurements at 175°

Figure 10 presents the frequency distribution of voltage measurements from the servo-controlled rheostat system at 170. The histogram reveals a well-defined distribution of values centered around 1.17-1.18 V, with frequencies reaching up to 154 counts at these voltage levels. The distribution exhibits a roughly symmetrical shape, suggesting minimal systematic bias in the measurements at this servo configuration.

TABEL 1. CALCULATION RESULTS

Metric	Rheostat rotation angle		Average
	175°	5°	
Sample Size (n)	369	369	-
Mean	3.878	1.176	-
Median	3.876	1.173	2.525
Standard Deviation (SD)	0.008	0.011	0.009
Minimum	3.83	1.16	-
Maximum	3.92	1.21	-
Range	0.09	0.05	0.07
Coefficient of Variation (%)	0.210	0.918	0.564

The observed voltage range and distribution characteristics demonstrate that the system maintains consistent performance across different operational conditions. The standard deviation of approximately 0.011 V and corresponding coefficient of variation (CV) of 0.918% remain within acceptable limits for most precision applications. The complete calculation results are summarized in Table 1.

Table 1 presents statistical analysis results from 738 measurement data points, with average value of standard deviation of 0.009. The data range is exceptionally narrow at average 0.07, while a average coefficient of variation (CV) of 0.564% indicates minimal relative variability. These metrics collectively demonstrate a tightly clustered dataset with strong central tendency and no significant deviations.

The exceptionally low standard deviation and CV, both well below 1%, provide robust evidence of high data stability [13-14]. In quality control terminology, these results approach Six Sigma capability (3.4 defects per million opportunities) [15]. Visual representation through a histogram would reveal a tall, narrow peak centered at 3.88 with short tails on either side, confirming the data's exceptional concentration around the mean.

Research on servo-controlled rheostats has various important applications, particularly in power and control systems [16]. One of their primary implementations is in renewable energy systems, such as solar power plants [17], where servo-controlled rheostats function as automatically adjustable loads to optimize maximum power point tracking (MPPT). They can also be used to trace the I-V curve of photovoltaic (PV) systems to identify their maximum power point [18-20]. Another application is in robotic inverse kinematic movement, where closed-loop control is essential for achieving high precision; the proposed device can be effectively utilized in such systems [21]. Additionally, these servo-controlled rheostats enable reactive power control in asynchronous generator-based power plants [22], reducing the reliance on dummy loads for output voltage stabilization.

IV. CONCLUSION

This research successfully demonstrates the feasibility and precision of a servo-controlled variable resistor system for modern electronic applications requiring programmable analog control. The system exhibits exceptional stability, as evidenced by comprehensive testing across 738 operational trials, which revealed remarkably consistent performance with a standard deviation of 0.009 V and an exceptionally narrow data range averaging 0.07. The coefficient of variation (CV) of 0.564% confirms minimal relative variability, meeting and exceeding the precision requirements. The demonstrated combination of mechanical reliability, electrical precision ($\sigma=0.009$), and programmability makes this servo-controlled approach particularly valuable for applications requiring remote adjustability, power system control, or adaptive circuit tuning in fields of industrial process control.

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