

The Design and Evaluation of a Microcontroller-Based Electromechanical Position Control System

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Abstract. This paper develops an integrated electromechanical position control system with an embedded microcontroller platform, combining signal processing, control, actuation, and mechanical design. The system operates through a sensing, control, and execution loop for automatic position adjustment. For hardware implementation, the system includes a signal conditioning circuit, a power drive circuit, and a mechanical structure for sensor processing, actuator control, and component integration. For control implementation, a proportional controller runs on an Arduino microcontroller for closed-loop position adjustment. Then, its performance is evaluated through circuit, control, and prototype simulations under different inputs. The results indicate that the prototype achieves a relative tracking error below 2% across the tested positions, with an average response time of 0.82 s under the 90° reference input. Moreover, the integrated hardware and software modules achieve basic closed-loop position control in a low-cost electromechanical prototype system.

Keywords: Electromechanical Position Control, Microcontroller-Based Control, Proportional Feedback Control, Signal Conditioning Circuit, Closed-Loop Control

1. Introduction

By integrating sensing, control, actuation, and mechanical structures, electromechanical systems are widely used in robotics, automation equipment, and motion control systems. With the advancement of control algorithms and embedded technologies, current systems have improved control accuracy and response performance. However, the integration of signal acquisition, circuit design, embedded implementation, and mechanical assembly into a low-cost prototype remains challenging, especially for educational applications [1, 2]. Therefore, this study presents the design and implementation of a microcontroller-based electromechanical position control system to examine how hardware and software modules can be combined to achieve automatic position adjustment through closed-loop feedback control. The proposed system integrates signal conditioning, actuator driving, proportional feedback control, and mechanical structure design, and its performance is evaluated through circuit simulation, control simulation, and prototype experiments under different reference inputs. Through this study, a basic closed-loop electromechanical system is implemented, providing a reference for future improvements such as applying more advanced control methods and testing under different operating conditions.

2. The system architecture and hardware-software design

2.1. The control system architecture

The proposed system enables automatic position adjustment via integrated sensing, computing, and actuation. Accordingly, the system was structured into three functional layers: the sensing layer, the control layer, and the execution layer [3, 4]. In this configuration, the sensing layer collects physical signals from the controlled object and transfers the measured information to the control layer. Based on the feedback information, the control layer generates a command from the position error and sends it to the execution layer. The received command is then converted into actuator motion by the execution layer to achieve the required displacement. This sensing-control-execution loop defines the closed-loop structure of the prototype system. This structure connects the hardware and software modules to achieve feedback-based position adjustment.

2.2. Hardware design for signal acquisition and actuation

The hardware system consists of three parts: the signal conditioning circuit, the power drive circuit, and the mechanical structure [5]. The signal conditioning circuit processes sensor signals, the power drive circuit drives the actuator, and the mechanical structure provides the required mounting and alignment for the hardware components.

For signal acquisition, the signal conditioning circuit filters sensor signals before microcontroller sampling. The raw sensor output may contain high-frequency noise and voltage fluctuations; thus, an RC low-pass filter is used for noise reduction. The cutoff frequency is given by:

$$f_c = \frac{1}{2\pi RC} \quad (1)$$

where R and C represent the resistance and capacitance, respectively. A voltage follower based on an operational amplifier is further added for impedance matching and stable signal transmission.

For actuator driving, the power drive circuit converts the microcontroller control signal into an actuator driving signal [5]. Since the microcontroller cannot supply enough current, transistors are used for switching and amplification. Additionally, a freewheeling diode is connected to suppress the reverse voltage generated by the inductive load during switching.

For hardware integration, the mechanical structure supports the installation of the sensor, control board, actuator, and transmission components [6-9]. For this purpose, CAD modeling is applied to design the frame and support parts, thus ensuring proper assembly and alignment of the hardware modules.

2.3. Embedded feedback control design

For position control, a proportional (P) controller reduces the position error between the reference value and the measured position [10, 11]. The controller adjusts the actuator command according to the error magnitude, enabling basic position control. The control input is defined as:

$$u(t) = K_p[r(t) - y(t)] \quad (2)$$

where $u(t)$ is the control input, K_p denotes the proportional gain, $r(t)$ is the reference position, and $y(t)$ is the measured output. Based on this model, the electromechanical system can be

described by a simplified second-order model to analyze the basic response characteristics:

$$J\ddot{\theta}(t) + B\dot{\theta}(t) + K\theta(t) = K_u u(t) \quad (3)$$

where J , B , and K represent the equivalent inertia, damping coefficient, and stiffness coefficient, respectively. K_u denotes actuator gain, and $\theta(t)$ denotes angular position. This model is applied to provide a simplified description of the system response [12].

The controller runs on an Arduino microcontroller. During operation, the microcontroller reads sensor feedback, calculates position error, and updates the actuator command at each sampling interval. The discrete control law is expressed as:

$$u_k = K_p(r_k - y_k) \quad (4)$$

where u_k is the control command at the k -th sampling instant, r_k is the reference signal, and y_k is the measured position [12]. Through repeated sampling and control updating, the microcontroller performs closed-loop position control.

3. The simulation and experimental verification of the control system

3.1. Simulation of circuit performance

Prior to the hardware implementation, circuit simulations evaluated the basic functions of the signal conditioning and power drive circuits. Specifically, the simulation mainly verified signal smoothing, voltage buffering, and actuator driving capability.

For the signal conditioning circuit, the input and output waveforms were compared to evaluate the RC low-pass filter and voltage follower. The filtered signal reduced high-frequency fluctuations and produced a smoother waveform for microcontroller sampling. In addition, the voltage follower maintained the output level and provided buffering between the sensor and control circuit.

For the power drive circuit, the simulation evaluated the switching operation and protection function of the actuator driver. The transistor-based circuit converted the Arduino control signal into a drive signal for the actuator. Meanwhile, the freewheeling diode suppressed voltage spikes from the inductive load during switching and protected the control circuit.

3.2. Simulation of closed-loop control performance

Under different gain settings, a second-order electromechanical model was applied to observe the proportional controller response. The simulation was performed to examine how the proportional gain affects the motion response and to select a suitable parameter for the prototype system.

With a low proportional gain, the system showed a slower response and a larger position error. Increasing the proportional gain improved the response speed but introduced larger overshoot and transient oscillations. After adjusting the gain within an appropriate range, the controller achieved a faster response with reduced oscillation and acceptable position tracking performance.

The simulation results guide the selection of the proportional gain for the prototype. The selected parameter offers a balance between response speed and stability, allowing the system to perform closed-loop position adjustment during operation.

3.3. Prototype experiments under different reference inputs

For prototype testing, a platform was developed using an Arduino microcontroller, an encoder, and a servo actuator. In this setup, the system was powered by a 5 V supply, and the control loop operated at a sampling frequency of 100 Hz. The experiments were then conducted under no-load conditions with a fixed proportional gain. To evaluate the basic positioning capability, a reference position of 90° was selected for repeated testing. Subsequently, five tests were performed under the same operating condition to examine positioning accuracy, response time, and repeatability. The experimental results are summarized in Table 1.

Table 1. Repeated prototype test results under 90° reference input

Test No.	Reference Position (°)	Measured Position (°)	Absolute Error (°)	Relative Error (%)	Response Time (s)
1	90.0	88.4	1.6	1.78	0.83
2	90.0	88.9	1.1	1.22	0.78
3	90.0	88.5	1.5	1.67	0.82
4	90.0	88.2	1.8	2.00	0.86
5	90.0	88.7	1.3	1.44	0.80

The five measurements resulted in an average measured position of 88.54°, with a mean absolute error of 1.46°, a mean relative error of 1.62%, and an average response time of 0.82 s. The position variation among repeated tests was mainly caused by actuator accuracy, mechanical clearance, and sensor measurement uncertainty. To examine the position tracking capability at different target locations, additional tests were conducted with reference positions of 60°, 90°, and 120°. These positions cover the main operating range of the prototype and represent different actuator travel distances. The average results are summarized in Table 2.

Table 2. Average performance under different reference inputs

Reference Position (°)	Average Measured Position (°)	Mean Absolute Error (°)	Relative Error (%)	Average Response Time (s)
60	59.1	0.9	1.50	0.68
90	88.54	1.46	1.62	0.82
120	118.1	1.9	1.58	0.97

Across the tested reference positions, the prototype maintained a relative tracking error below 2%. And the response time increased slightly with larger reference positions due to the increased actuator movement distance. These results show that the prototype can perform position adjustment across the tested operating range.

3.4. The repeatability evaluation of prototype response

The repeated measurements under the 90° reference input were further analyzed to evaluate the consistency of the prototype response under identical operating conditions. Since the target position, control gain, and load condition were kept unchanged during these tests, the variation among

measurements mainly reflects the influence of actuator accuracy, mechanical clearance, and sensor measurement uncertainty [3].

The standard deviation of the measured position was 0.26° , while the standard deviation of the response time was 0.03 s. The small position variation shows that the actuator returned to a similar final position in repeated trials, while the limited response time variation shows that the control loop maintained a consistent response process. During the repeated experiments, no obvious oscillation, response loss, or abnormal fluctuation was observed. The repeatability evaluation demonstrates that the prototype can provide similar position adjustment results under the same reference input and operating conditions. These observations indicate that the prototype produced consistent position adjustment results under the same reference input and operating conditions [1, 2].

4. Integrated evaluation of system performance

4.1. Hardware-software system integration

Upon completion of the separate testing procedures for each module, the sensing, control, driving, and mechanical components were assembled into the complete prototype system. In this system, the sensing module acquired position feedback, which was processed by the Arduino microcontroller to generate actuator commands. Meanwhile, the driving circuit converted control signals into actuator inputs, while the mechanical structure supported component installation and motion transmission.

During integration, the hardware and software modules were connected through the sensing, control, and execution loop. The prototype was operated under the same control process used in the experiments, including signal acquisition, control calculation, actuator driving, and mechanical movement. The operation results showed that no communication interruption, actuator malfunction, or structural interference was observed during operation, indicating proper system integration.

4.2. Performance assessment of the integrated system

The performance of the integrated system was assessed based on the prototype experiments under different reference positions. Moreover, the evaluation focused on whether the combined hardware and software modules could achieve automatic position adjustment through the closed-loop control process. The main results at 60° , 90° , and 120° reference inputs are summarized in Table 3.

Table 3. Performance assessment of the integrated system under different reference inputs

Reference Position ($^\circ$)	Average Measured Position ($^\circ$)	Mean Absolute Error ($^\circ$)	Relative Error (%)	Average Response Time (s)	Stability Observation
60	59.1	0.9	1.50	0.68	Stable
90	88.54	1.46	1.62	0.82	Stable
120	118.1	1.9	1.58	0.97	Stable

Across the tested reference positions, the prototype achieved a relative position error below 2%, indicating that the sensing, control, and actuation modules worked together to perform automatic position adjustment. Meanwhile, the response time increased with larger position changes due to longer actuator travel. Figure 1 shows the tracking error variation during position adjustment under different reference inputs. After the reference position changed, the error increased due to the

difference between the target and measured positions. The feedback controller then reduced the error through continuous command updates. Also, no continuous oscillation or increasing error trend was observed during the tests.

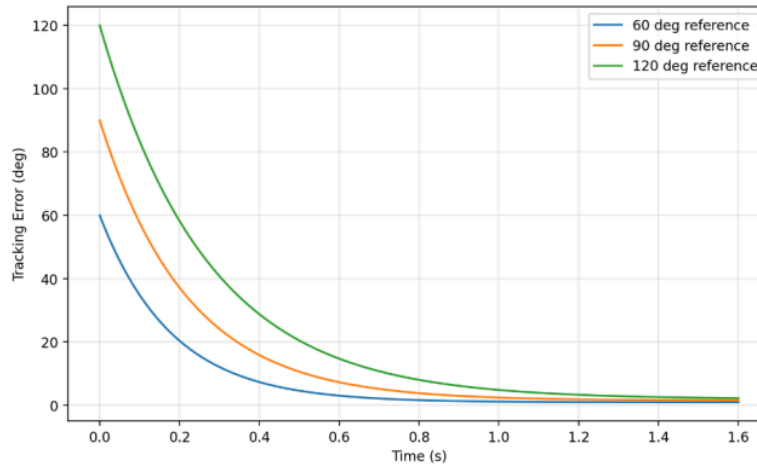


Figure 1. Tracking error curves under different reference inputs

4.3. System applications and future improvements

By integrating signal acquisition, embedded control, actuator driving, and mechanical transmission, the proposed system forms a compact electromechanical prototype. The simulation and results show that the system can perform basic signal processing, closed-loop position adjustment, and repeated operation using a low-cost embedded platform. Therefore, the prototype can be used for educational demonstrations, basic robotics experiments, and introductory studies of automatic control systems.

However, the controller uses proportional feedback, which reduces position error but cannot eliminate steady-state error. PID or adaptive control methods can be introduced to improve response performance. In addition, the experiments were conducted under no-load conditions, and the system response may change when external loads, friction variations, or different mechanical conditions are introduced. Moreover, the current design also explores prototype-level position control rather than high-precision industrial applications. Future work may include testing advanced control algorithms, expanding experimental conditions, and improving the hardware design. These developments can provide further experience in embedded control, robotics, and mechatronic system design [1, 12].

5. Conclusion

This study presented the design and implementation of a microcontroller-based electromechanical position control system. The proposed system integrates signal acquisition, proportional feedback control, actuator driving, and mechanical structure into a complete sensing–control–execution loop. The circuit simulations evaluated the basic functions of the signal conditioning and power drive circuits before hardware implementation. The control simulation was used to observe the influence of proportional gain on system response and to select a suitable parameter for prototype operation. Experimental results under different reference positions showed that the prototype could achieve automatic position adjustment through closed-loop feedback control, with a relative tracking error below 2% and an average response time of 0.82 s under the tested conditions. The prototype achieved the expected position control function using a low-cost embedded system. Although the current design is limited by the proportional controller and no-load testing condition, the results

confirm that the developed hardware and software modules can work together to realize basic closed-loop position adjustment.

References

- [1] Sánchez, C., Sánchez, D., & Rodríguez-Morales, R. A., et al. (2022). Lab-Tec@Home: A cost-effective kit for online control engineering education. *Electronics*, 11(6), 907.
- [2] Muñoz, J., Monje, C. A., Mena, L. K., et al. (2022). Educational low cost platform for control engineering. In *XLIII Jornadas de Automática: libro de actas* (pp. 295-301). <https://doi.org/10.17979/spudc.9788497498418.0295>
- [3] Vazquez-Santacruz, J. A., Portillo-Velez, R., Torres-Figueroa, J., et al. (2023). Towards an integrated design methodology for mechatronic systems. *Research in Engineering Design*, 34(4), 497–512.
- [4] Chu, C. Y., Zhang, C. J., & Yin, C. F. (2024). Synchronous integration method of mechatronic system design, geometric design, and simulation based on SysML. *Computer-Aided Design*, 174, 103735.
- [5] Yuce, E., & Minaei, S. (2025). Basic electrical circuits. In *Fundamentals of Electronics: Circuit Analysis and Amplifier Design* (pp. 1-52). Springer Nature Switzerland.
- [6] Ikubanni, P. P., Adeleke, A. A., Agboola, O. O., et al. (2022). Present and future impacts of computer-aided design/computer-aided manufacturing (CAD/CAM). *Journal Européen des Systèmes Automatisés*, 55(3), 349–357.
- [7] Gerschütz, B., Sauer, C., Kormann, A., et al. (2023). Digital engineering methods in practical use during mechatronic design processes. *Designs*, 7(4), 93. <https://doi.org/10.3390/designs7040093>
- [8] Țîțu, A. M., & Pop, A. B. (2024). Implementation of CAD/CAM/CAE systems for improved design and manufacturing processes in industrial organizations. *Proceedings of the International Conference on Business Excellence*, 18(1), 3069–3078. <https://doi.org/10.2478/picbe-2024-0253>
- [9] Simonič, M., Palčič, I., & Klančnik, S. (2025). Advancing intelligent toolpath generation: A systematic review of CAD–CAM integration in Industry 4.0 and 5.0. *Strojniški vestnik-Journal of Mechanical Engineering*, 71(9-10), 328-336. <https://doi.org/10.5545/sv-jme.2025.1370>
- [10] Akash, R. K. (2025). Comparative analysis of control strategies for position regulation in DC servo motors. *arXiv preprint*. <https://arxiv.org/abs/2501.11820>
- [11] Debnath, D. (2022). Position control of a DC servo motor using various controllers. *Materials Today: Proceedings*, 62, 5131–5137. <https://doi.org/10.1016/j.matpr.2022.04.735>
- [12] Mistry, H., Laila, D. S., & Foo, M. (2023). Teaching embedded control system design of electromechanical devices using a lab-scale smart farming system. *International Journal of Mechanical Engineering Education*, 53(2), 391–410.