Stabilization Control System for Dielectric Elastomer Actuators

Research Report

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Stabilization Control System for Dielectric Elastomer Actuators

by

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Preface

The journey of researching stabilization control systems for dielectric elastomer actuators has been both challenging and rewarding. During this project, I became fascinated by the potential of DEAs to mimic natural muscle movements.

I am profoundly grateful to my supervisor, Stefania Konstantinidi, whose expertise and encouragement were instrumental in guiding this project. I also extend my appreciation to my professor, Dr. Yves Perriard, for his invaluable guidance. This work would not have been possible without the resources and support provided by them.

I would like to thank the entire LAI lab who helped me throughout my summer research project. I am also grateful to EPFL and the Laidlaw Foundation for the opportunity I received.

This report presents a comprehensive study of DEAs, starting with their fundamental principles, moving through modeling and control strategies, and culminating in experimental validations. Navigating the complexities of voltage control systems and material non-linearities offered invaluable learning experiences.

Undertaking this research has reinforced my passion for engineering innovation, and I am excited to contribute to the growing body of knowledge in this field. I hope that the findings herein will serve as a foundation for future advancements in DEAs and their applications.

Raki Ben Mustapha
EPFL, October 2024

Abstract

Dielectric elastomer actuators have emerged as promising components in soft robotics and biomedical engineering. This research aims to enhance the reliability and movement quality of DEAs used to replace the zygomaticus muscle, enabling individuals with facial paralysis to smile again. We propose a model for anisotropic viscoelastic dielectric elastomers, which is employed to describe the actuator's dynamic response and design a closed-loop Proportional-Integral-Derivative control system for precise actuation of the facial prosthesis. Electromyography signals were collected from the healthy side of subjects' faces to drive the DEAs on the affected side. The control system demonstrated its efficacy in minimizing error and improving actuation performance compared to EMG signals recording movement of the zygomaticus major muscle responsible for smiling. The findings demonstrate that the PID-controlled DEAs accurately mimic natural muscle movements, significantly improving actuation precision and stability.

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Introduction

Facial paralysis is a significant medical condition that affects an individual's ability to control the muscles of the face, thereby impairing essential functions such as expressing emotions, speaking, and even basic motor tasks like blinking and chewing. This condition severely compromises both the physical appearance and the quality of life of the patient. Conventional treatments for chronic or severe facial paralysis typically involve invasive surgical procedures, most notably the two-stage free muscle transfer technique, which entails harvesting muscle tissue from another part of the body and grafting it to the affected area. Although effective, this approach is associated with prolonged recovery times, potential complications, and a lengthy rehabilitation process.

In light of these challenges, researchers have been exploring less invasive alternatives, focusing on the development of artificial muscles that can closely mimic the natural movement of facial muscles. These synthetic muscles, designed to replicate the biomechanical properties of natural tissue, hold the potential to restore facial function without the need for complex surgical interventions.

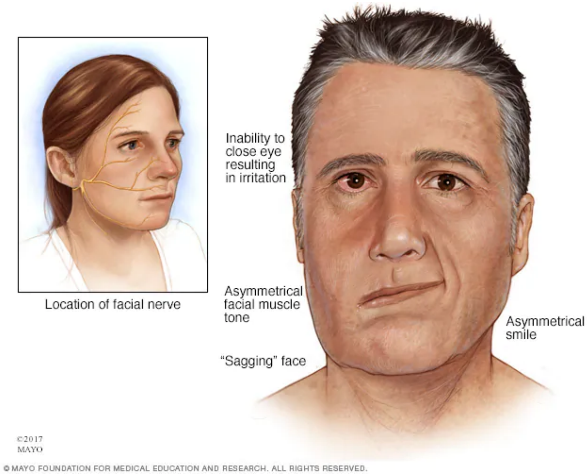


Figure 1.1: Facial paralysis[7]

A notable advancement in the field of artificial muscle development is the implementation of dielectric elastomer actuators (DEAs)[4]. These innovative materials have the ability to generate movement through electrical stimulation, offering a flexible and efficient way to replicate the behavior of natural muscles.

1.1. Dielectric Elastomer Actuators

A **Dielectric Elastomer Actuator (DEA)** is a type of soft actuator that converts electrical energy into mechanical motion, often described as an ”artificial muscle.” DEAs work based on the principle that applying a voltage across a dielectric elastomer (a flexible, insulating material) causes a reduction in thickness and an increase in surface area, generating motion.

How DEAs Work

DEAs are typically constructed as a **compliant capacitor**, with a dielectric elastomer layer sandwiched between two flexible electrodes. When a voltage is applied, the positive and negative charges accumulate on the electrodes, creating an electric field. This generates a pressure called **Maxwell stress**, which causes the elastomer to compress in thickness while expanding in its other dimensions.

The capacitance of the DEA can be expressed as:

$$C = \frac{\varepsilon_0 \varepsilon A}{z} \tag{1.1}$$

Where:

- ε_0 is the permittivity of free space,
- ε is the relative permittivity of the material,
- A is the area of the electrodes,
- z is the thickness of the dielectric elastomer.

The **Maxwell stress**, which leads to the actuation of the elastomer, is given by:

$$p = \varepsilon_0 \varepsilon E^2 = \varepsilon_0 \varepsilon \left(\frac{V}{z}\right)^2 \tag{1.2}$$

Where:

- E is the electric field,
- V is the applied voltage.

As the elastomer compresses under this stress, it experiences strain in the thickness direction while expanding in the plane of the electrodes. The **thickness strain** is defined as:

$$s_z = -\frac{\varepsilon_0 \varepsilon E^2}{Y} \tag{1.3}$$

Where Y is the **elastic modulus** of the material.

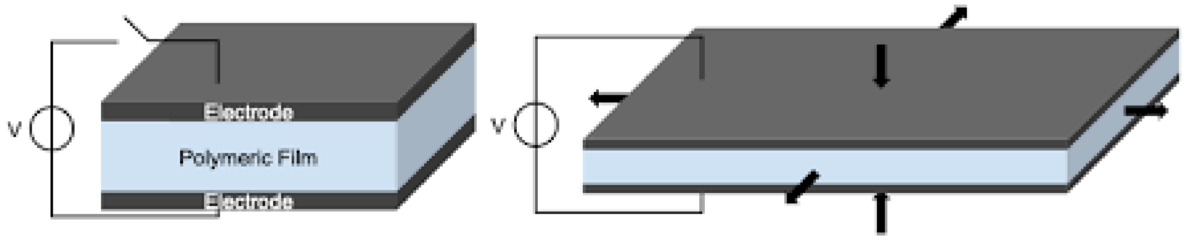


Figure 1.2: Working principle of a DEA[6]

Key Advantages of DEAs

DEAs offer several advantages over traditional actuators:

- **Large Actuation Strain**: Capable of strains over 100%, allowing for significant deformation.
- **High Energy Density**: Energy densities can exceed 3.4 MJ/m^3, making them efficient.
- **Fast Response Time**: Can respond in milliseconds, suitable for dynamic applications.

Material Considerations

For optimal DEA performance, the elastomer should have:

- A low elastic modulus (to enable large deformations),
- High dielectric constant (to increase actuation strain),
- High electrical breakdown strength (to withstand high voltages).

Common materials used in DEAs include **silicones**, **acrylics**, and **polyurethanes**. Silicones, for example, offer better operational stability at high frequencies and is more suitable to implement in the human body [2].

Operating Voltage Considerations

One of the main challenges with DEAs is their requirement for high operating voltages, typically ranging from 3 kV to 10 kV, depending on the polymer used and the film thickness. However, operating at high voltages can be advantageous in certain cases, as it allows for lower currents, which reduces energy losses in wires and electrodes.

2

Methodology

Since the DEA is an actuator, it can have many sources of errors that prevent it from achieving the expected value of displacement it needs. To address these challenges and achieve smooth and lifelike movements under voltage, we adopted a straightforward methodology focused on replicating real-life conditions and developing an effective control system. The key steps in our approach are:

1. **Setup Creation**

   We designed an experimental setup that simulates real-life conditions, particularly the movements of facial muscles. This setup includes factors like friction, mechanical constraints, and external forces that affect the actuator's performance. By closely mimicking these conditions, we ensured that our findings would be applicable in practical scenarios.

2. **System Identification**

   We performed system identification to understand how the DEAs behave within our setup. This involved figuring out the transfer function that describes the movement of the DEA due to the voltage input.

3. **Modeling the Control System**

   Using the insights gained from system identification, we developed a control system model that represents the actuator's behavior. This model helps predict how the actuator will respond to various control inputs and allows us to design a control strategy that can achieve the desired smooth movements.

4. **Testing and Tuning**

   We implemented the control system and conducted tests to evaluate its performance. By observing how the actuator responded under different conditions, we were able to tune the control parameters to improve accuracy and smoothness. This iterative process involved adjusting the control system based on test results to enhance performance.

5. **Refining**

   Based on the testing and tuning outcomes, we refined the control system and the setup to better match the desired behavior of the actuators. This step ensures that both the model and the physical setup accurately represent the system, allowing for more precise control and improved replication of lifelike movements.

3

Setup Creation

3.1. Facial Anatomy

The muscle that will be working on is the *zygomaticus major*[5].

- **Location**: The zygomaticus major is a facial muscle that extends from the cheekbone to the corner of the mouth on each side of the face.
- **Origin**: It originates from the lateral surface of the *zygomatic bone* (cheekbone).
- **Insertion**: The muscle inserts into the *corner of the mouth* (modiolus), pulling it upward and outward.
- **Length**: Typically, the zygomaticus major measures about **5 to 6 centimeters** in length.
- **Function**: It is primarily responsible for elevating the corners of the mouth, enabling expressions like smiling.

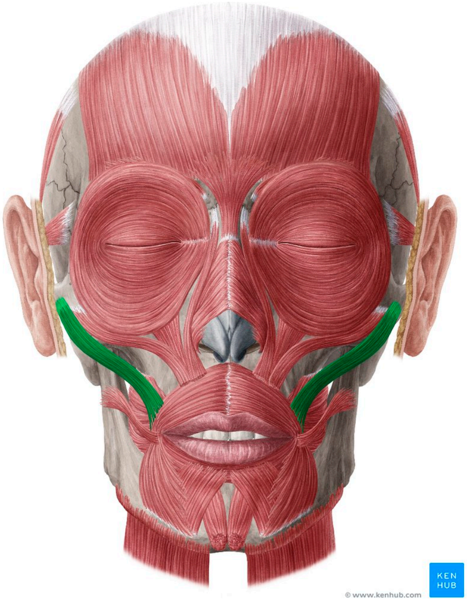


Figure 3.1: zygomaticus major

The DEA will be positioned to replicate the function of the zygomaticus major muscle, as shown in the image. The DEA will be placed along the same path as the zygomaticus major, anchored near the zygomatic bone (cheekbone) and extending down toward the corner of the mouth. This positioning allows the DEA to mimic the natural movement of the zygomaticus major, pulling the corners of the mouth upward, effectively simulating facial expressions such as smiling. By aligning the DEA with the muscle's anatomical location, we can create a more realistic and functional facial muscle movement.

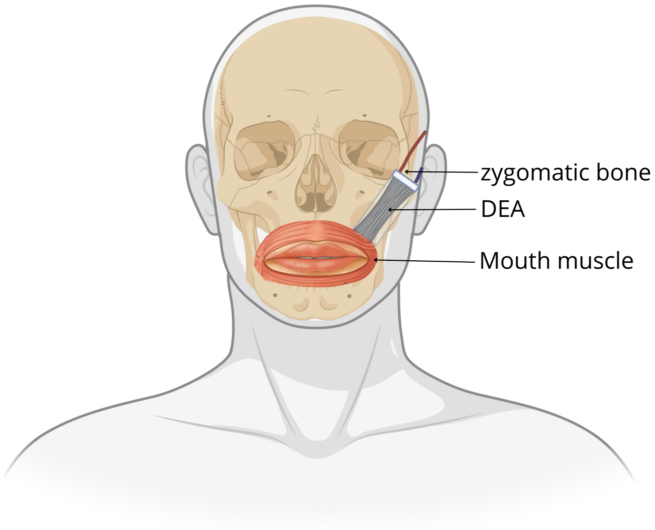


Figure 3.2: DEA Placement

3.2. First setup:

Before developing the control system, the initial objective was to design an experimental setup that closely simulates the real-world application of the dielectric elastomer actuator (DEA) in the face. The first attempt involved a vertical setup, which consisted of a DEA anchored by two supports with a weight attached to its lower end. This arrangement allowed the DEA to undergo displacement when voltage was applied. A laser system was employed to precisely measure this displacement, which provided essential feedback to the control system.

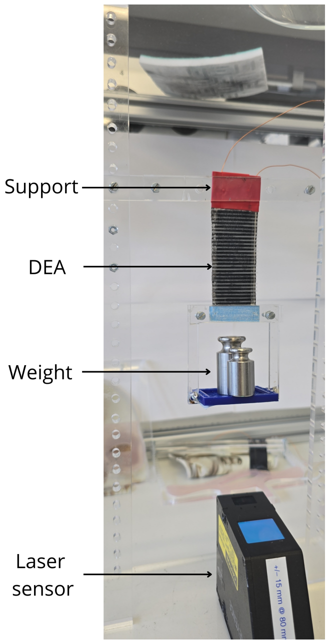


Figure 3.3: Vertical setup

Pros	Cons
• Easy tuning of the control system. • No friction affecting movement, leading to smoother operation. • Easy to calculate exact displacement using a laser.	• The setup does not represent real-life constraints and conditions. • Limited applicability to real-world scenarios, reducing practical relevance.

Table 3.1: Pros and Cons of the Vertical Setup

3.3. Final setup:

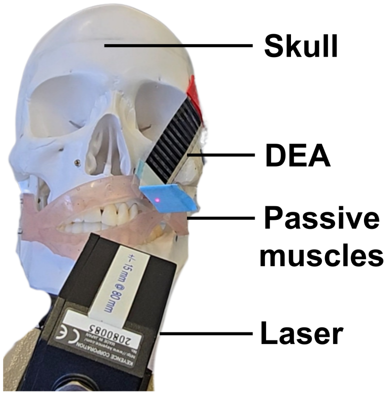


Figure 3.4: Skull setup

This setup represents an improvement over the initial vertical configuration by more accurately simulating the real-life conditions of DEA in the face.

Skull: Instead of a simplified vertical arrangement, this setup uses a skull model to more closely mimic the anatomical structure of the human face. The skull provides a realistic and rigid support structure, similar to how facial muscles interact with bone, particularly the zygomatic bone, where the zygomaticus major originates.

DEA: The DEA is now positioned anatomically along the path of the zygomaticus major muscle, replicating the real muscle's role in lifting the corner of the mouth. This setup allows the actuator to move in a way that mirrors the actual contraction of the muscle, offering a more accurate representation of facial expressions like smiling compared to the basic vertical setup.

Passive Muscles: These components represent non-active parts of the facial muscle system. Their inclusion in the setup adds a layer of realism by showing how the active DEA interacts with the surrounding muscle structures, a feature that was missing in the vertical setup where only the DEA and weight were involved.

4

System Identification

We employed two methods to determine the transfer function of the DEA system:

1. Physical Equation Method

In this approach, the transfer function was determined by analyzing the system dynamics based on the physical characteristics of the DEA. Using fundamental principles of mechanics and electrical behavior,the governing equations that describe the relationship between the input voltage and the resulting displacement of the actuator were derived. These equations were then solved to express the system's behavior in the form of a transfer function.

2. MATLAB System Identification Tool

For a more empirical approach, I also utilized the *System Identification Tool* available in MATLAB. This method involved gathering experimental data from the DEA system, where various voltage inputs were applied, and the resulting displacements were recorded. Using this data, I applied the system identification toolbox in MATLAB to estimate the system's transfer function.

The toolbox uses algorithms to fit a mathematical model to the experimental data, automatically generating a transfer function that best matches the observed behavior of the DEA. This method provided a practical, data-driven model that reflects the actual performance of the system under real-life conditions.

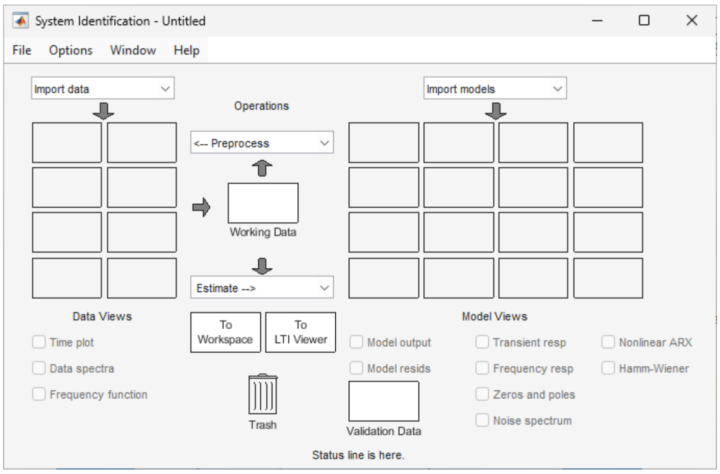


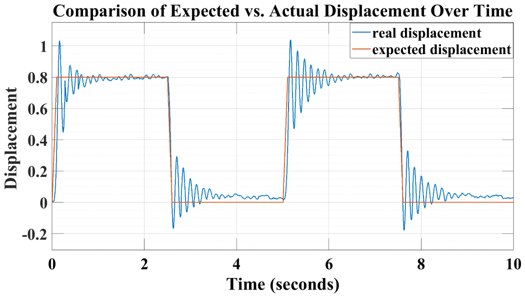
Figure 4.1: System identification tool

5

Control System

5.1. Setups error analysis

5.1.1. Vertical setup



In the results shown in the graph below, which were obtained using a rectangular signal in the vertical setup, the output response generally follows the input trend but displays significant deviations, oscillations, and delays. Two types of errors can be observed:

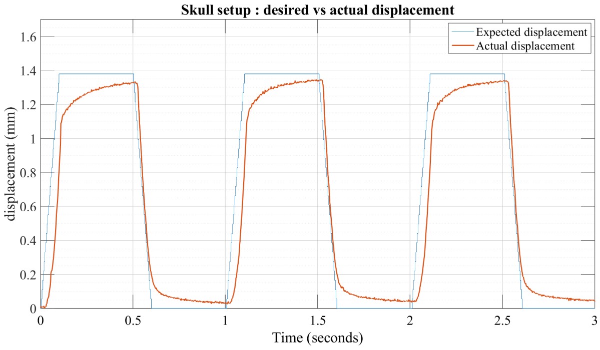
1. Overshoot Error:

Overshoot is characterized by pronounced oscillations before eventually stabilizing near the desired position. This occurs when the output initially exceeds the target value due to the system's response to a sudden change in input, resulting in a peak that is higher than the desired setpoint.

2. Steady-State Error:

Steady-state error is the residual difference between the desired setpoint and the actual output after the system has stabilized. Even after the transient effects subside, the system may not exactly reach the target, leading to a persistent error. Reducing steady-state error is crucial to achieving accurate, long-term performance.

5.1.2. Skull setup



The skull setup exhibited a different response compared to the vertical setup. Due to friction, the displacement output did not experience overshoot; however, it had a poor response time to the input and a significantly large steady-state error.
To address these errors, **a control system** is being implemented.

5.2. What is a control system?

A **control system** is a system designed to regulate the behavior of a device in order to achieve a desired output or performance. It continuously monitors input signals (in our case voltage) and adjusts the system's output to maintain a specific objective, like maintaining stability, tracking a target value, or responding to changes in the environment.

A control system typically consists of:

- **Sensors** to measure the current state of the system (input).
- **Controller** to process the input data and determine the necessary adjustments.
- **Actuators** to implement the controller's decisions and change the system's behavior (output).

There control system we are using the closed loop system as it adjusts its actions based on feedback from sensors (e.g. laser sensor) that measure the system's current state, allowing the system to correct deviations and maintain desired performance.

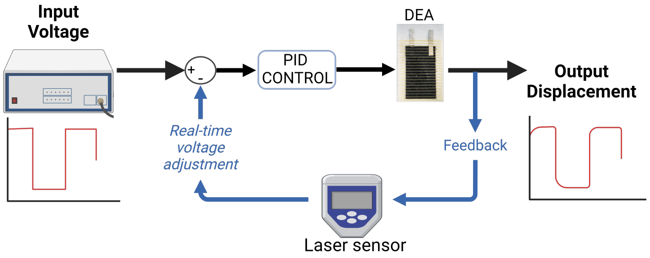


Figure 5.1: A closed-loop control system

One of the most known control systems is : **PID control**

5.3. PID control

A **PID (Proportional-Integral-Derivative) controller** is a widely used control system that combines three control actions to ensure the desired behavior of a system. It adjusts the system's input based on the difference between the desired setpoint and the actual measured output. The controller uses three terms to calculate the corrective action: the **Proportional** term (P), the **Integral** term (I), and the **Derivative** term (D).

The general equation for the control signal $u(t)$ in a PID controller is:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{d}{dt} e(t)$$

Where:

- $e(t) = r(t) - y(t)$ is the error, the difference between the reference or setpoint $r(t)$ and the measured output $y(t)$.
- K_p is the proportional gain, which determines the magnitude of the proportional term.
- K_i is the integral gain, which determines the magnitude of the integral term.
- K_d is the derivative gain, which determines the magnitude of the derivative term.

Components of PID Control:

- **Proportional (P)**: The proportional term is directly proportional to the current error. It provides an immediate corrective action to reduce the error. The equation is:

$$u_P(t) = K_p e(t)$$

- **Integral (I)**: The integral term accounts for the accumulation of past errors. It corrects for any residual error that the proportional term alone cannot eliminate, helping to reduce the steady-state error. The equation is:

$$u_I(t) = K_i \int_0^t e(\tau) d\tau$$

- **Derivative (D)**: The derivative term anticipates future error based on the rate of change of the error. It helps to improve system stability and reduce overshoot by dampening the system's response to fast changes in error. The equation is:

$$u_D(t) = K_d \frac{d}{dt} e(t)$$

My task was to fine-tune the PID controller by selecting the optimal values for the proportional (P), integral (I), and derivative (D) coefficients. The goal was to achieve a balance between system stability and responsiveness. By carefully adjusting these parameters, I aimed to minimize errors such as overshoot and steady-state error, while ensuring the system responded as quickly as possible to input changes. This involved iterative testing and adjustments to find the ideal combination that would result in both smooth and accurate control of the DEA's movements.

6

Results

After extensive testing and tuning, the results proved to be quite satisfying. Through careful adjustment of the PID coefficients, the system exhibited significantly improved performance.

6.1. Eliminating Overshoot Error

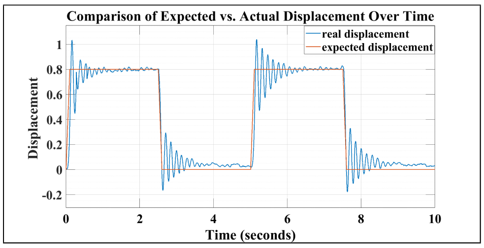


Figure 6.1: Before tuning

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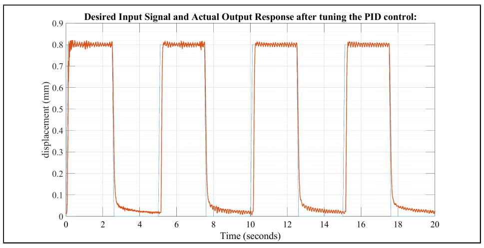


Figure 6.2: After tuning

Implementing the PID control on the vertical setup successfully eliminated the overshoot error, leading to a more stable system. The actuator's response became more controlled, avoiding the initial peaks that previously exceeded the desired setpoint.

6.2. Enhancing Response Time

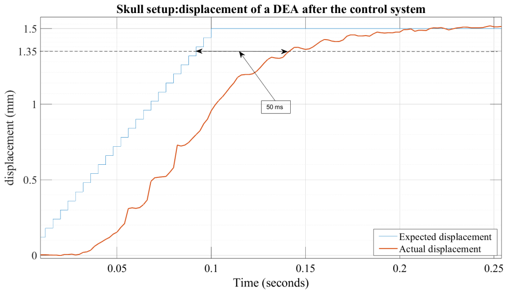
The **response time** of a control system refers to the time it takes for the system to reach and stabilize near its desired output after a change in the input. It is typically measured as the time required to reach a specific percentage (commonly 90% to 95%) of the final value, depending on the system requirements.

Mathematically, response time t_r can be defined as:

$$t_r = t_{95\%} - t_{0\%}$$

Where:

- $t_{95\%}$ is the time at which the system reaches 95% of the final value.
- $t_{0\%}$ is the time when the input signal is first applied (typically $t = 0$).

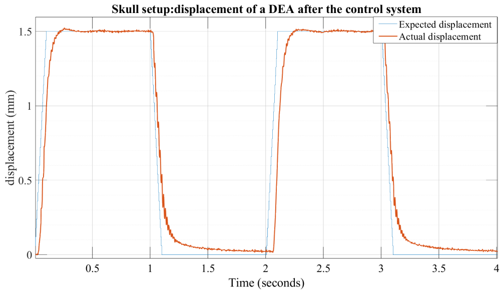


In the skull setup, the response time of the system showed significant improvement after tuning the PID controller. The results are summarized in the table below:

Condition	Response Time (ms)
Before Tuning	400 ms
After Tuning	50 ms

Table 6.1: Response Time Before and After Tuning

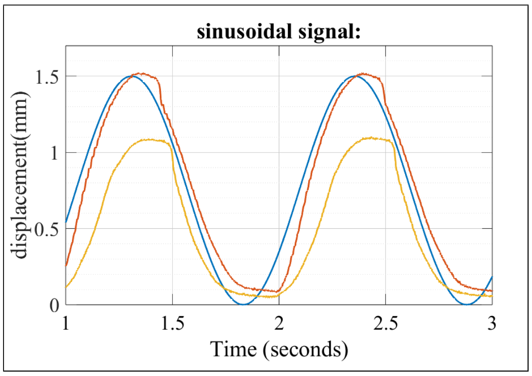
6.3. Overall System Performance

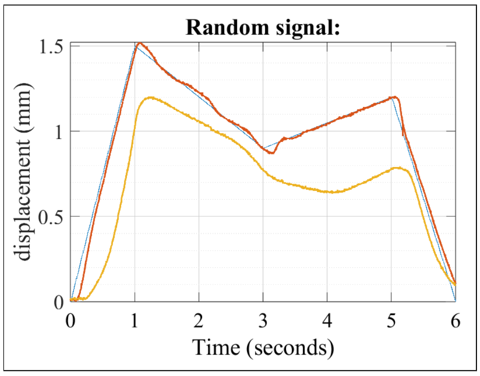


The final result for the step signal in the skull setup, shown in the graph above, demonstrates a significant improvement in the system's performance after tuning the control system. As we can see, the actual displacement (represented by the orange line) closely follows the expected displacement (represented by the blue line). This indicates that the control system is accurately regulating the DEA's response, with minimal deviation from the target value.

6.4. Response to different signals

To ensure the quality and robustness of the PID control system, we subjected it to a variety of test signals. By analyzing the system's behavior under different conditions, we aimed to verify whether the controller consistently delivered accurate and stable responses across all signal types.





In the two graphs shown above, the blue line represents the expected value, the yellow line corresponds to the output before tuning, and the red line reflects the output after tuning. To quantify the accuracy and quality of our results, we calculated the Root Mean Square Error (RMSE). RMSE provides a clear metric for evaluating the difference between the expected and actual values over time, allowing us to measure the overall performance of the system. By calculating the RMSE, we could objectively assess how well the tuned control system tracks the desired output, providing insight into how effectively the PID controller minimizes errors throughout the system's response.

RMSE	Sinusoidal Signal	Random Signal
Before PID	0.3528	0.3173
After PID	0.1445	0.0494

Table 6.2: RMSE Before and After PID for Different Signals

The RMSE values before and after applying the PID controller clearly show a significant improvement in the system's performance.The reduction in error demonstrates that the PID controller effectively minimizes deviations from the expected output, leading to more precise and stable system behavior across both types of signals. The results confirm the success of the tuning process in achieving a more accurate response.

7

Future Capabilities

Exploring Advanced Control Models Beyond PID

To further enhance performance, exploring alternative control models beyond traditional PID is essential. One promising approach is the implementation of advanced control algorithms, such as neural networks, which have the ability to learn and predict muscle movements. By training neural networks on human muscle movement data, we can achieve greater control precision, potentially leading to faster and more accurate replication of muscle behavior compared to PID control. These adaptable and responsive control systems are better equipped to mimic natural muscle dynamics, offering improved performance in applications where traditional control methods may fall short.

Self-sensing DEA

One promising future capability is the development of self-sensing DEAs [1][3], which would eliminate the need for external sensors such as laser displacement sensors. Self-sensing DEAs are designed to monitor their own deformation by measuring changes in their electrical properties, such as capacitance, as they expand or contract. This built-in sensing capability would not only simplify the system but also reduce the overall cost, improve compactness, and enhance the system's response time. By integrating actuation and sensing into a single device, self-sensing DEAs could lead to more efficient and intelligent control systems, paving the way for more advanced applications in robotics, prosthetics, and other areas requiring precise, real-time feedback.

8

Conclusion

The project successfully demonstrated the potential of dielectric elastomer actuators (DEAs) in replicating complex muscle movements, particularly for facial paralysis applications. By fine-tuning the PID controller, we achieved significant improvements in response time, stability, and accuracy, proving that DEAs can effectively mimic natural muscle dynamics. These advancements offer a promising foundation for integrating DEAs into rehabilitation technologies, particularly for patients suffering from facial paralysis, where precise and responsive muscle control is critical for restoring natural facial expressions.

Looking ahead, future advancements in control models present exciting possibilities for further enhancing the performance of DEA-based systems. By exploring more advanced algorithms, such as neural networks and adaptive control strategies, we could achieve even greater precision and responsiveness. These control models have the potential to not only improve the replication of muscle movements but also to allow for systems that can learn and adapt over time, making them highly suitable for dynamic and personalized rehabilitation applications.

Ultimately, the combination of DEAs and advanced control technologies paves the way for more effective, natural, and life-enhancing applications in rehabilitation, prosthetics, and beyond, offering hope for improved quality of life for individuals affected by neuromuscular impairments.

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