Exploring Puppetry through Robotics

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Introduction

The art of puppetry has traditionally revolved around the direct manipulation of inanimate figures to create the illusion of life. In conventional forms, such as hand or rod-operated puppets, the puppeteer's physical connection to the puppet is critical to conveying nuanced movements and lifelike performance. This project explores the possibilities of breaking that physical connection through the use of robotics and remote control technologies. By doing so, the performer can operate a puppet from a distance, while the puppet itself remains in the world of the performance space and conveys the performance in real time.

This project integrates computer science, robotics, and design to build a working prototype of a remote puppet — one that explores the boundaries of traditional puppetry techniques while preserving lifelike movement. Here, lifelike movement refers to a performance that an audience will be willing to suspend their disbelief for, to accept that the puppet on stage is the true performer. The goal for this project was to design a robotic puppet skeleton that could be remotely controlled from a distance, through manipulating a smaller-scale version of itself. This tele-operation approach allows the puppeteer to maintain real-time control over the puppet's movement, while expanding on the possibilities of what constitutes a performer's presence on stage.

Motivation

The inspiration for this project arose from the intersection of computer science and theatre, two fields that, at first glance, appear disparate but share a deep connection through storytelling and problem-solving. Puppetry, as an art form, challenges performers to imbue life into static figures, relying heavily on mechanics, design, and movement. While puppeteers traditionally work in full view of the audience, their artistry often emphasizes the puppet over their own presence.

Remote puppetry, as explored in this project, draws parallels to technologies like animatronics in theme parks and virtual digital puppetry. However, these existing implementations often involve preprogrammed movements or digital avatars, rather than real-time interaction in the physical world. The challenge presented here was to develop a robotic puppet capable of nuanced and lifelike movements without relying on preprogrammed behaviors. The project investigates new ways to achieve the illusion of life, exploring:

1. How to create a puppet that conveys lifelike movement through remote operation.
2. Whether the puppet needs to resemble a humanoid or living form to evoke a sense of realism.
3. How the absence of a performer on stage impacts the audience's perception of the puppet.

This project serves as a foundation for further exploration of remote performance technologies and their implications for modern puppetry, robotics, and live theatre.

Research Background

The art of puppetry, as one of the earliest performance forms, has often explored the delicate boundary between the animate and inanimate. Puppets traditionally rely on direct human manipulation to generate lifelike movements, combining the performer's skill with the puppet's mechanical design. This reliance on direct control contrasts with advancements in automation, animatronics, and robotics that strive for autonomy and independence in movement while replicating lifelike expressiveness.

Animatronics in King Kong on Broadway

The Broadway production of *King Kong* represents a milestone in animatronics and puppetry, demonstrating how lifelike movement and expressiveness can be achieved through the integration of advanced robotics and human collaboration. Created by Creature Technology Co., the animatronic Kong stood 20 feet tall and weighed approximately 2,000 pounds, incorporating a steel and carbon-fiber skeleton with synthetic materials for "muscles" and "skin." This construction allowed the puppet to achieve realistic motion while balancing structural stability and aesthetic design [1].

Kong's movements were controlled by a combination of onstage and offstage operators. A team of 10 onstage puppeteers manipulated Kong's limbs and facial expressions using physical inputs, while an offstage crew managed the intricate internal robotics, ensuring seamless integration of human input and mechanical precision. The goal of this project was to produce a scaled down version of this, where a robotic arm prototype was designed to be manipulated remotely, translating the performer's input into lifelike movements in real-time.

Expressive Movement and Lifelike Animation

Expressive movement plays a pivotal role in both puppetry and robotics. Heinrich von Kleist's observations on marionettes highlight the inherent balance puppeteers achieve between control and the puppet's physical dynamics. As Kleist argued, the puppet's "soul" lies in its pendular motion, which emerges naturally from its center of gravity rather than precise replication of human movement [3]. We considered that puppetry does not only feature humans or humanoid creatures, and thus a puppet does not necessarily require human features to be a believable "live" creatutre.

Masahiro Mori's concept of the *uncanny valley* further contextualizes the significance of movement in lifelike animation. Mori postulated that the affinity humans feel for inanimate objects diminishes as objects become increasingly humanlike but fall short of true realism [4]. While robotics and animatronics often risk falling into the uncanny valley by overemphasizing realism, traditional puppets, such as Bunraku marionettes, balance abstraction with familiarity to maintain their expressive qualities [7].

The use of indirect control systems, such as marionette strings or rods, further enables puppetry to abstract movement rather than precisely imitate it. Puppeteers rely on a combination of artistry, improvisation, and intuition to translate human motion into puppetry's simplified yet expressive dynamics. Engineers exploring robotic puppets have adopted a similar philosophy, recognizing that expressive movement does not require perfect replication of human kinematics [6].

Automated and Tele-Operated Puppetry Systems

Contemporary research in robotic puppetry draws heavily on the principles of human-operated marionettes while integrating advanced technologies like motion capture and real-time controllers. Projects such as the *Pygmalion Project* illustrate the transition from human-driven puppetry to automated systems. In this project, motion-capture choreography recorded from human performers was translated into robotic control systems capable of animating marionettes [8].

Optimal control strategies have been developed to manage marionette strings and controllers, allowing robots to approximate lifelike motions indirectly. Instead of mimicking human movements, these systems abstract motion to achieve expressive results, similar to the "Imitate, Simplify, Exaggerate" approach used in traditional puppetry [5]. This highlights the potential for robotics to emulate puppetry's artistic qualities while addressing its technical challenges.

Technological Challenges

While robotic puppetry introduces opportunities for expanding the boundaries of performance, it also presents unique challenges. Early experiments with robotic marionettes often faced difficulties in achieving stability, fluidity, and range of motion. Fixed robotic arms, for instance, struggled to replicate the dexterity and dynamism of human puppeteers [2]. More flexible systems incorporating magnetic wheels and dynamic winches offered solutions by increasing mobility and control precision [9].

However, real time tele-operation remains a critical area of exploration. Tele-operated systems, which allow performers to manipulate robotic puppets remotely, bridge the gap between direct human control and autonomous animation. These systems combine the intuitive nature of human input with the scalability and flexibility of robotics, making them particularly relevant for live theatre applications.

Avoiding the Uncanny Valley in Puppet Design

A recurring theme in robotic puppetry research is the avoidance of the uncanny valley. Unlike autonomous robots, puppets inherently acknowledge the presence of a human operator, allowing audiences to project life onto inanimate objects without the discomfort associated with near-human forms. As Mori observed, Bunraku puppets successfully evoke a sense of affinity by abstracting human movement rather than attempting to replicate it precisely [4].

By leveraging this principle, robotic puppets can avoid the pitfalls of uncanny aesthetics. Puppetry's ability to balance abstraction and expressiveness provides a model for designing robotic systems that prioritize movement dynamics over visual realism.

Research Insights

The key insights from this research can be summarized as follows:

- Puppetry excels at creating the illusion of life through expressive, abstracted movements rather than precise mimicry of human behavior.
- Mori's concept of the uncanny valley emphasizes the importance of avoiding hyper-realistic design in robotic puppets to maintain audience affinity.
- Real-time tele-operation combines the benefits of human intuition with robotic scalability, offering new possibilities for live performance.
- Indirect control systems, such as those used in marionettes, provide a framework for designing robotic controllers that prioritize expressive movement over mechanical precision.

These findings provide a foundation for the exploration of robotic puppets that are capable of nuanced, lifelike movement without preprogrammed behaviors. By integrating the artistry of puppetry with advancements in robotics, this project seeks to expand the boundaries of traditional performance and reimagine the role of the puppeteer in a technologically mediated context.

Project Objectives

The primary objectives of this project were as follows:

1. Design and build a prototype robotic puppet that can be controlled remotely.
2. Develop a control mechanism that allows for nuanced and lifelike movements without pre-programming.
3. Investigate how the visual design of the puppet (e.g., humanoid vs. abstract form) influences the audience's perception of realism.
4. Present the puppet in a live demonstration to evaluate the feasibility of real-time remote manipulation.

Methodology

Conceptual Design

The project began with the conceptualization of a robotic puppet that acts as a "skeleton" capable of lifelike movement. Unlike traditional puppets, this robotic structure would be controlled remotely by a performer operating a smaller-scale version of the same mechanism. This approach allows the puppeteer's gestures to directly translate into movements of the full-scale puppet in real time.

The shape and overall design of the robotic agent is reminiscent of an arm, complete with an adjustable grip. The arm was considered as a suitable baseline to create a robotic agent for due to the following reasons: There exists various designs of robotic arms to seek inspiration from, the joints along the "arm" provides the robotic agent multiple degrees of freedom, with the option for scaling up in the future. In addition, we considered the simplistic nature of the common hand puppet, where an arm can be used to represent heads, mouths, or arms of the puppet.

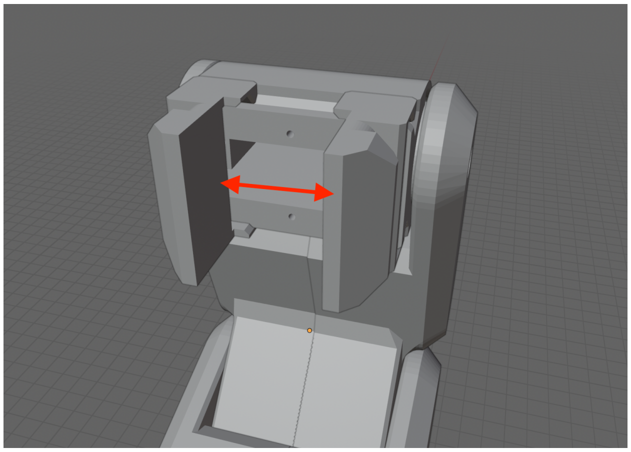
The puppet's skeleton would consist of a robotic arm that could be later customized with foam or other materials to form a puppet "skin." This modular approach ensures flexibility in the puppet's appearance and allows for experimentation with both humanoid and non-humanoid designs.

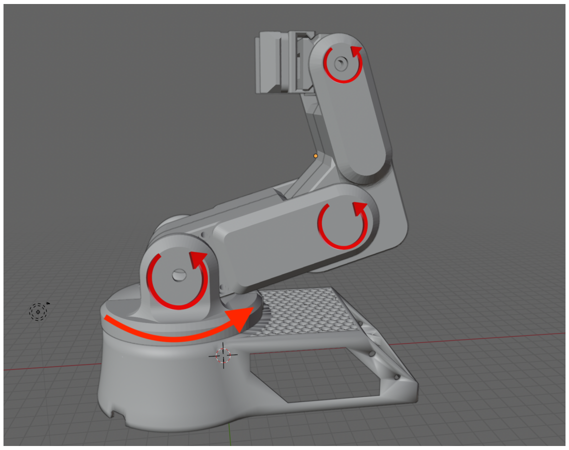
Technical Development

Design of the Puppet Skeleton

The prototype robotic arm served as the foundational skeleton of the puppet. Its design accounted for the fact that it needed enough range of motion to properly emulate lifelike movements, yet should not get caught on other materials used to dress the puppet.

3D Modeling - Puppet design

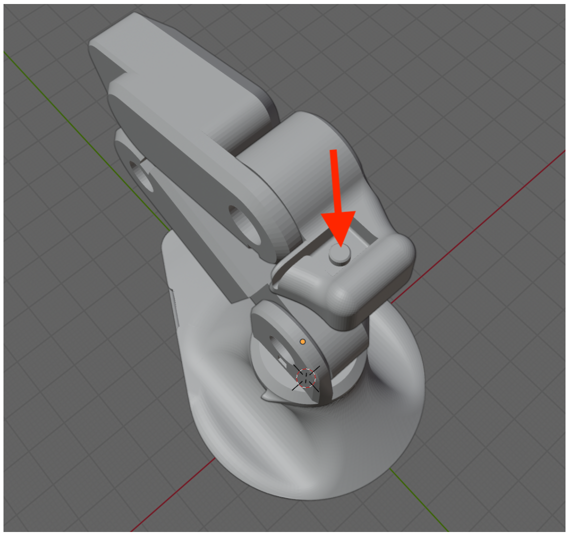


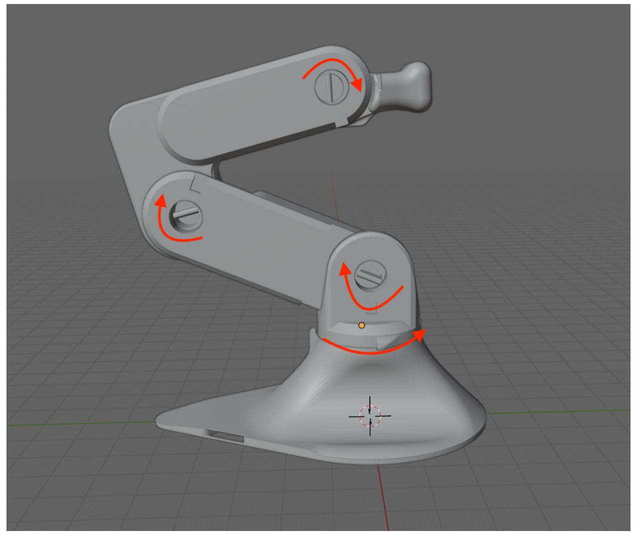


The robotic arm components are shown here in Blender, a 3D modelling software, where each component is a 3D model to be printed separately and reassembled with screws.

This design prioritizes joint flexibility, modularity, and lightweight construction to ensure smooth movement. In addition, the cabling of each of the motors would be run within the puppet, rather than outside, down into a base for a cleaner look.

Control Mechanism - ”Mini” version





A smaller-scale version of the robotic arm was to be constructed for the puppeteer to manipulate.

Real-time control would be achieved through a combination of sensors and actuators that mirrored the movements of the smaller arm onto the full-scale puppet skeleton. The microcontroller, a small computing system, would be used to manage input signals from the smaller arm and output signals to the full-scale arm.

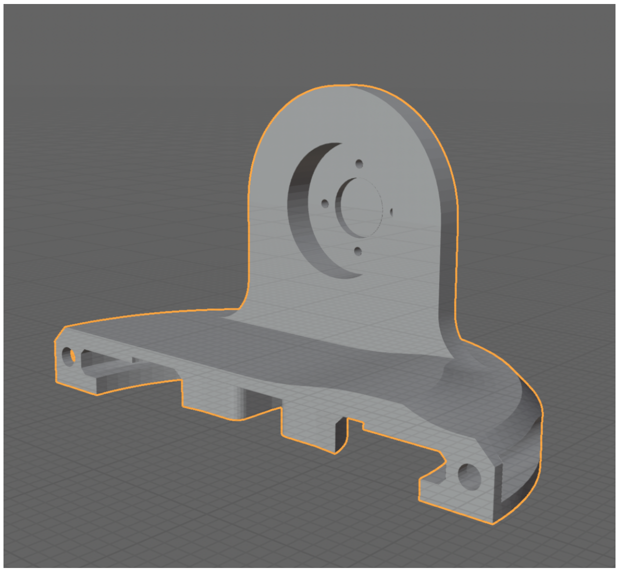
For example, the actuator at a joint (marked with curved red arrows above) detects motion that is monitored by a microcontroller that lives in the base of the puppet.

In the prototype, this monitoring is done by wiring the actuators on the controller directly to the microcontroller. However, it is also possible to use Bluetooth to link the two devices, allowing for a truly remote approach without need of concealing wires between the two systems.

Depending on the angle that the actuator on the controller it is moved, the recorded input is scaled with the progam on the microcontroller, which sends the ”translated” command to the puppet, allowing the scaled motion to be reflected on the ”real” puppet. A button (left) is used in place of the grip, where toggling the switch opens or closes the grip.

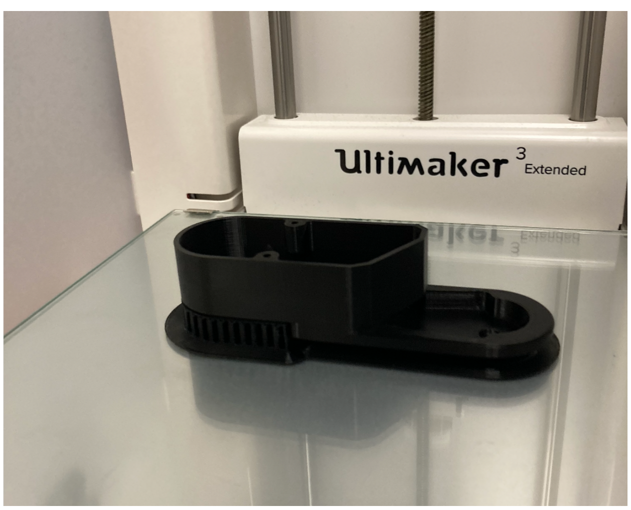
3D Printing

Model vs print



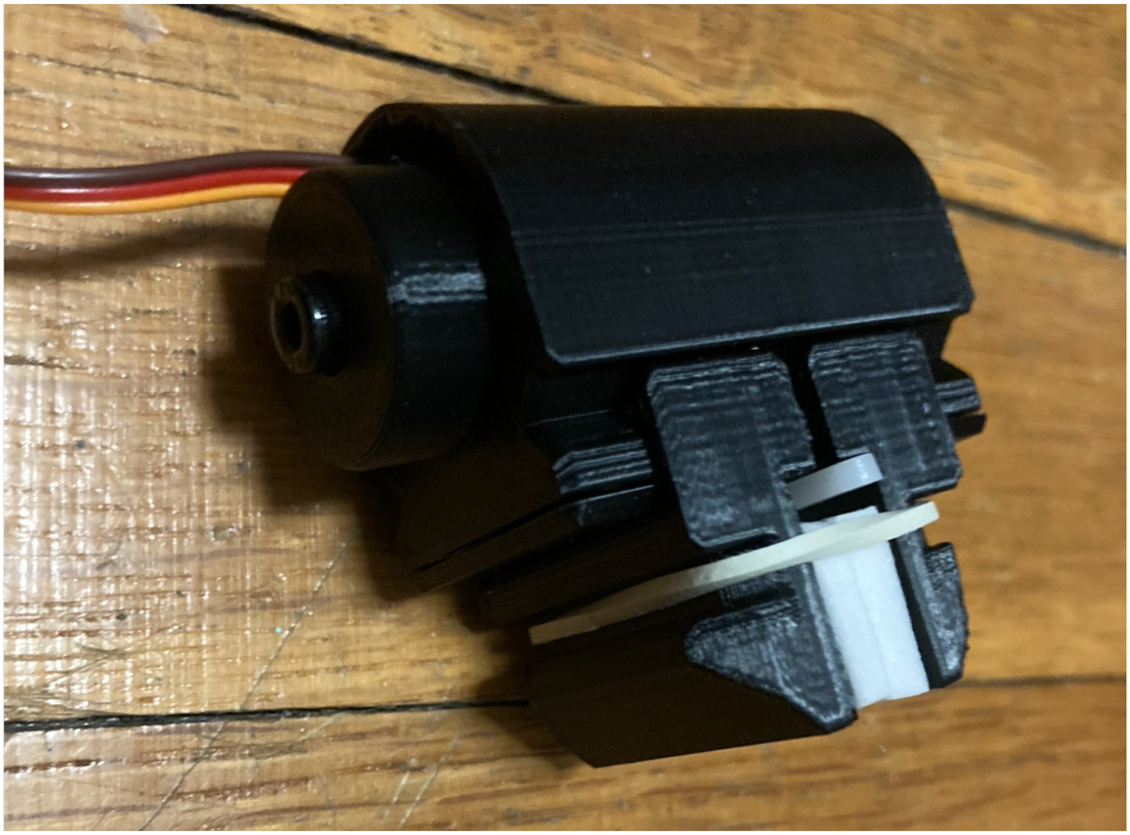
The modeled parts were 3D printed to create prototypes. The use of 3D printing allowed for rapid prototyping and iterative design improvements based on testing results. For example, the design of non-symmetrical pieces took some trial and error for printing, as the orientation of the print affected the speed of completing the print, and amount of wasted filament in terms of support during printing. This is due to the fact that the print is constructed from the bottom and upward in layers, and a print cannot happen in midair, thus needing to print blocks of support under the "true" print. Depending on the precision of the printer, its ability to print at at angles is also limited.

Efficient print vs Non efficient print

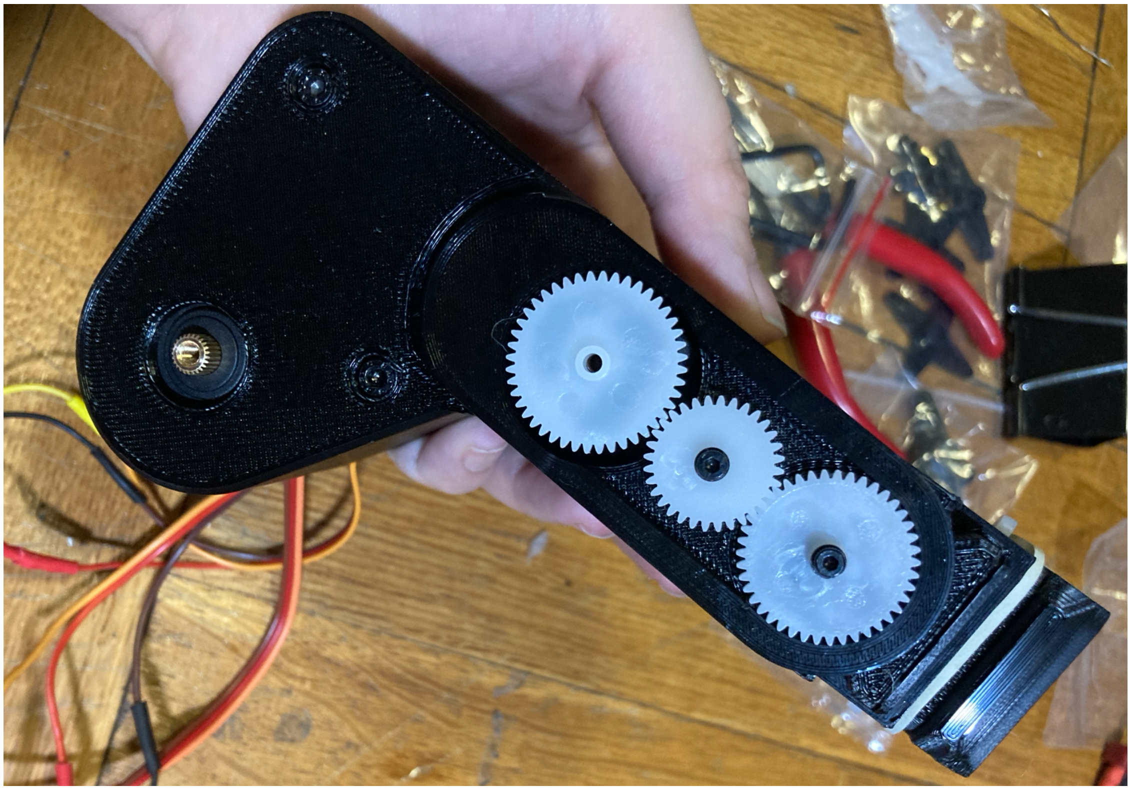


There was often a trade off in making some intuitive decision about the orientation to print it in which saves on the wasted filament, but is more difficult to remove from the true print, and affects the finish of the print (left). Opting for printing with the support "under" the piece allows to conceal the imperfections that arise from removing the support (right).

The Components



The Gripper was held together with a rubber band – triggering the servo (motorized device that rotates with precision controlled by a microcontroller), which sits inside the "head" shown above. The servo is attached to a plastic servo horn, a mechanical attachment that fits onto the shaft of a servo motor to transfer rotational motion. In between the two grips, the servo horn turns sideways, pushing the two grips apart along the track they sit on. Returning the lever to its vertical state, the pressure from the rubber band pushes the two grips back together.



A look at the gears that control the top two joints. Underneath are individual servos that can be adjusted programmatically.

The servo is the block with the purple tag, and the servo horn is the plastic cross sits on top of it. This sits below a 3D printed part with catches that lock on the servo horn, allowing the main body of the puppet to be rotated programmatically.

The Challenge

A grave miscalculation in the amount of slack the wires needed for the puppet to achieve full range of motion without, quite literally, ripping itself apart. we then extended the wires, but had not foreseen needing double the space for wires to run through the inside of the puppet, and thus the puppet with the multiple extended wires could not be assembled. The unfortunate fix for this is to remodel and reprint the puppet with more space within its joints. Another potential fix is to find new servos with much longer wires, but through this experience we found that there was little to no space for error, even with the unextended wires. A concern about the latter fix would be about broken wires requiring replacing the entire servo.

Results

The virtual prototype demonstrates the feasibility of remotely controlling a robotic puppet skeleton in real time, by using tools such as microprocessors and servos. Had the puppet been completed, the robotic arm's movements, while mechanical in structure, would have exhibited a range of natural and fluid motions, reinforcing the illusion of lifelike performance. The puppet skeleton would also have allowed for future customization, including the addition of foam or fabric to create a more expressive puppet design.

It remains an untested hypothesis that the absence of the performer on stage does not diminish the impact of the puppet's movements. Instead, the audience's focus might remain on the puppet, reinforcing the performer's artistry through indirect manipulation.

Discussion

This project set out to explore the feasibility of creating a **remote-controlled puppet** capable of conveying lifelike movement without direct manipulation by a performer on stage. By combining robotics, 3D modeling, and mechanical design, the prototype aimed to blur the lines between traditional puppetry and modern technological innovation.

The process demonstrated several successful outcomes:

1. **3D Modeling and Printing**: The robotic arm components were efficiently designed and iteratively tested using 3D printing. This modular design allowed for flexibility, lightweight construction, and opportunities for future customization.

2. **Control Mechanism Design**: The smaller-scale robotic arm control mechanism effectively demonstrated the principle of real-time input-output mirroring. By using servo motors and microcontrollers (Arduino), movement at one scale could be programmatically reflected at another scale.

However, the project encountered challenges that prevented the full-scale assembly of the puppet:

- A **miscalculation in wire slack** created significant mechanical issues. The wires, critical for transmitting signals to the servo motors, required more space within the joints to accommodate the full range of motion. Extending the wires resolved part of the issue but rendered the puppet's internal structure too constrained for assembly.

- These unforeseen physical constraints underscore the complexity of integrating electronic and mechanical systems in a compact design.

While the robotic arm remained incomplete, the virtual prototype demonstrated the plausibility of achieving lifelike movements through remote control, even though it remains to be tested in a physical performance setting. This partial success suggests that further refinement could push the project closer to its intended outcome.

Conclusion

The development of a robotic puppet skeleton operated remotely by a smaller-scale controller highlights the potential of integrating robotics into puppetry to create novel forms of performance. Although incomplete, the project succeeded in:

1. Establishing a modular and flexible mechanical design using 3D modeling and printing.

2. Developing a proof-of-concept control mechanism capable of mirroring movement in real time.

This work offers insights into the challenges of balancing mechanical design, electronic constraints, and the nuanced artistry of lifelike puppetry. The inability to complete the full assembly due to wire slack limitations emphasizes the importance of accounting for physical constraints early in the design process.

Despite these challenges, the project demonstrated that robotics could be leveraged to reimagine puppetry without compromising its fundamental goal: **creating the illusion of life.**

Future Work

Several opportunities exist to extend and refine this project in the future:

1. **Redesign for Wire Management**:
    - Increase the internal space within the puppet's joints and body to allow adequate slack for wiring without obstructing movement.
    - Explore alternative wire-routing techniques or flexible cable carriers to prevent tangling or strain.
2. **Testing and Performance**:
    - Complete the physical build of the robotic puppet skeleton to validate the real-time mirroring of lifelike movements.
    - Conduct live demonstrations to assess audience perception, specifically focusing on the impact of the performer's physical absence from the stage.
3. **Enhancing the Control Mechanism**:
    - Improve the smaller-scale controller for better ergonomics and precision.
    - Integrate more advanced sensors to enable smoother and more intuitive motion control.
4. **Aesthetic and Expressive Customization**:
    - Add foam, fabric, or other materials to enhance the puppet's visual expressiveness.
    - Experiment with humanoid and non-humanoid designs to evaluate audience perception of realism and lifelike movement.

The completion and refinement of this project would provide valuable insights into the integration of robotics and puppetry, paving the way for future explorations in remote performance technologies.

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