A Novel Supernumerary Robotic Limb for Human Augmentation:
Utilizing Soft Robotic Systems, a Tendon-Actuated Continuum Arm, and Dual-Layered Control Strategy

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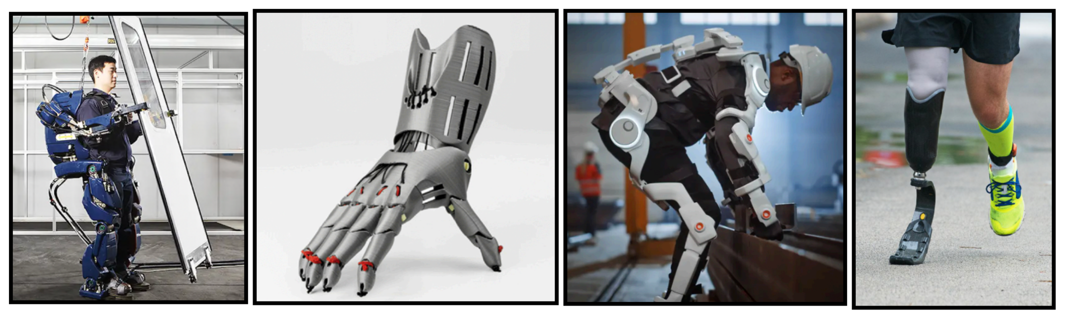
Problem Statement

- **1 in 2 workers in physically demanding occupations**—construction workers, first responders, military personnel, and high-risk laborers—**experience debilitating occupational injuries.**
- **41% of first-responders** report stress/strain based injuries due to their physical responsibilities within their occupation
- The American **construction industry sees 6,000 injuries** related to overexertion and job-related physical movement.

Background

Supernumerary Robotic Limb (SRL): a wearable robotic arm that acts as an extra limb for a user, giving them functionality beyond their existing human schema.

Rather than replacing existing limbs like exoskeletons and traditional prosthetics, SRLs are additional limbs attached to the user's upper body, designed to enhance functionality rather than restore lost movement. SRLs function independently, allowing users to perform tasks they could not achieve with their natural limbs alone.

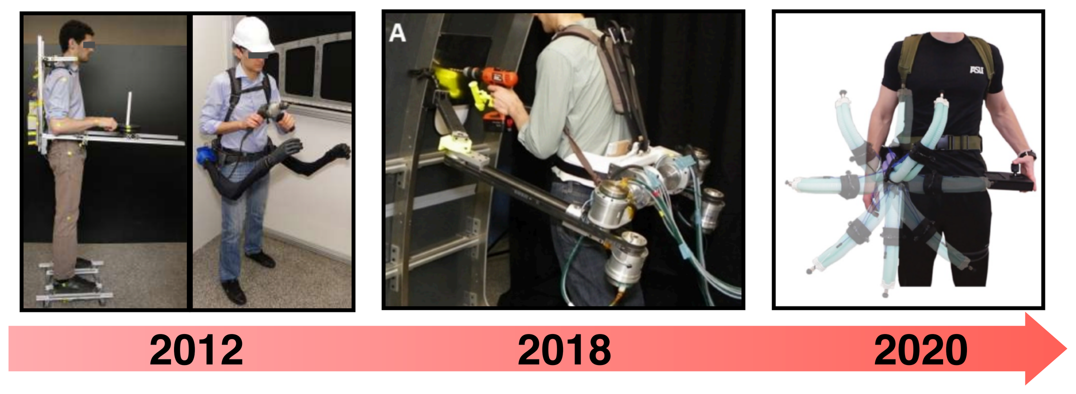


Current wearable robots are not usable in every-day environments and situations.

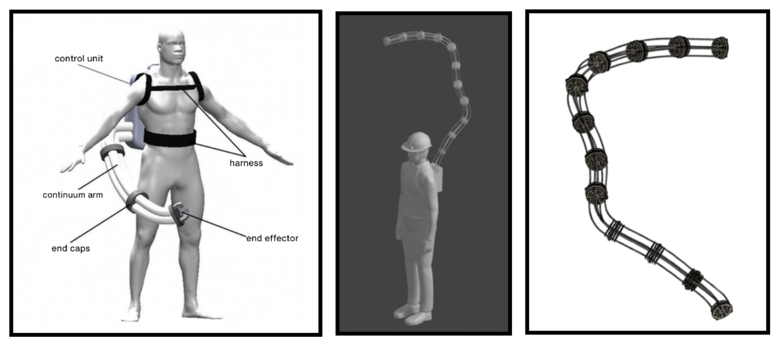
Reliance on Rigid Structures: most wearable robot designs use rigid, heavy mechanical components, which can be uncomfortable for extended use and undynamic in real-world scenarios.

Energy Efficiency & Portability: Many current SRLs require bulky power sources and tethered setups, limiting their real-world usability.

Limited Adaptability: Most studies focus on controlled lab environments rather than real-world applications such as industrial work, first response, or healthcare.



Solution and Research Objective



Address limitations in wearable robotics by developing a soft supernumerary robotic limb with multimodal control and usability.

1. **Soft, Tendon-Actuation:** Unlike rigid robotic arms, this design uses soft materials for increased flexibility, safety, and adaptability in human environments. Infinite degrees of freedom
2. **Discrete Cosserat Model:** To predict the movement of unconventional materials like silicon, cosserat rod theory is employed for full system efficiency and accuracy in any scenario.
3. **Lightweight & Portable Design**: Aims to create a wearable SRL that minimizes bulk while maintaining functional strength and dexterity.
4. **Intention Prediction:** Limiting the cognitive load on the user, minimizing distraction and lead time for the original task

Design Criteria & Constraints

Criteria	Constraints
○ Segments optimized for 45°±10 bending angles ○ Have a payload of 15±5 pounds. ○ Complete basic object manipulation and object avoidance	○ The arm must not interfere with the user's arm's natural motion/general movement ○ Materials will be complaint enough to help reduce injury in the risk of a collision ○ The supernumerary limb system should cost less than $350
○ The control unit should weigh <15 pounds ○ Distributes the weight on body	○ The entire system should not be a physical burden to the user ○ Structural failure should be safeguarded
○ The Cosserat Continuum model should reach less than 5% error ○ Overall movements should have <5cm of error ○ Intention should be predicted 80%	○ Largely autonomous and does not provide a substantial cognitive load to the user ○ System will immediately respond to external commands and stimuli

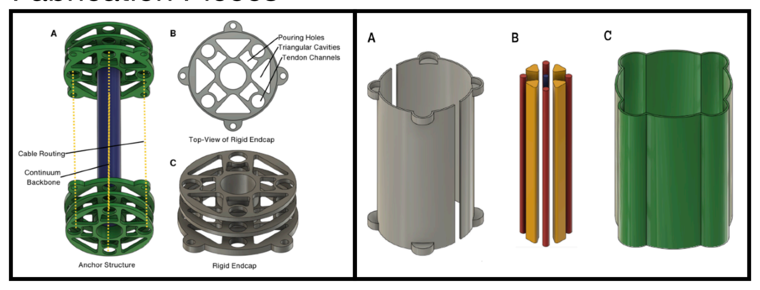
Soft Continuum Arm Design and Fabrication

Prototype 1: Continuum arm modeling a human spine, using rigid vertebrae and air tubing.

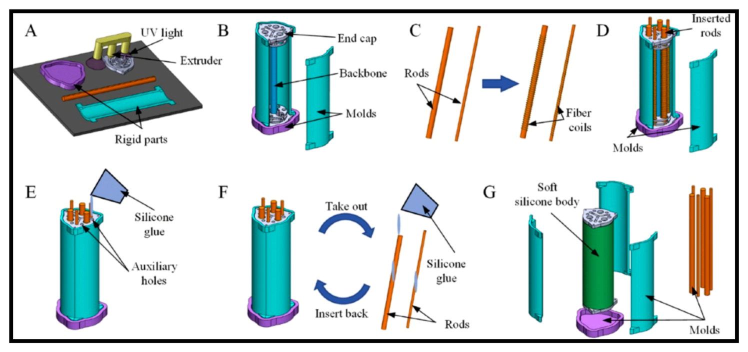
Prototype 2: Soft, origami-inspired wings between rigid vertebrae.

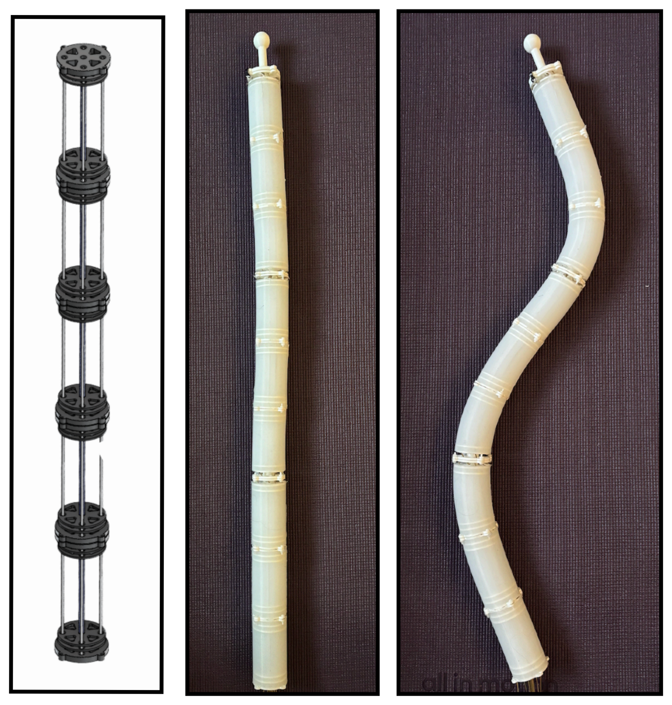
Prototype 3: Octopus-inspired segments using a rigid anchor structure and a soft, silicon body.

Fabrication Pieces

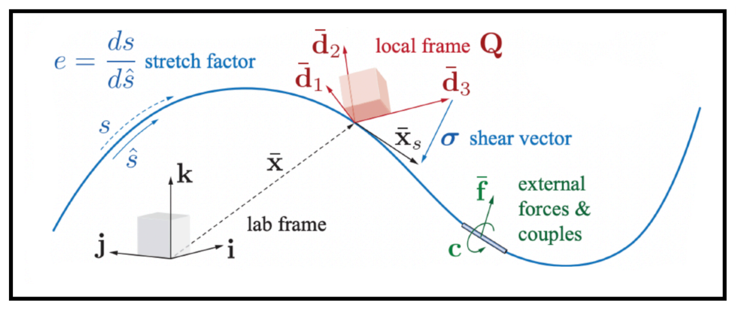


Fabrication Process





Discrete Cosserat Modeling for Limb Path Planning

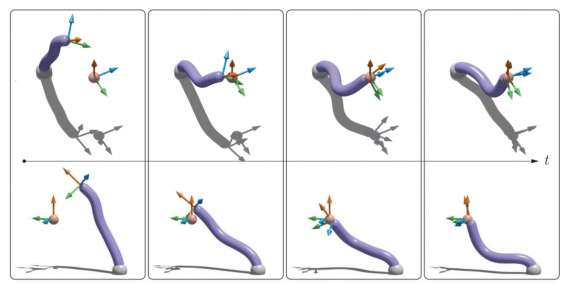


$$\rho A \cdot \partial_t^2 \bar{\mathbf{x}} = \partial_s \left(\frac{\mathbf{Q}^T \mathbf{S} \boldsymbol{\sigma}}{e} \right) + e \bar{\mathbf{f}}$$

$$\frac{\rho \mathbf{I}}{e} \cdot \partial_t \boldsymbol{\omega} = \partial_s \left(\frac{\mathbf{B} \boldsymbol{\kappa}}{e^3} \right) + \frac{\boldsymbol{\kappa} \times \mathbf{B} \boldsymbol{\kappa}}{e^3} + \left(\mathbf{Q} \frac{\bar{\mathbf{x}}_s}{e} \times \mathbf{S} \boldsymbol{\sigma} \right) + \left(\rho \mathbf{I} \cdot \frac{\boldsymbol{\omega}}{e} \right) \times \boldsymbol{\omega} + \frac{\rho \mathbf{I} \boldsymbol{\omega}}{e^2} \cdot \partial_t e + e \mathbf{c}$$

Dynamics of a slender body, formulating the linear and angular balance at every cross section of the arm.

Cosserat Renders to be reflected on the continuum arm

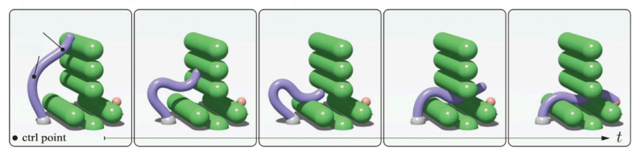


Path progression to a randomized point through obstacles

The 3-segmented continuum arm leveraging the modeled obstacles to maneuver through the opening and reach the target point. Averaged 6.3 seconds from linear state to point.

Path progression to a randomized point

The 3-segmented continuum arm makes its progression toward the point and its subsequent reorientation. Fixed to a predetermined origin.



Full System Assembly

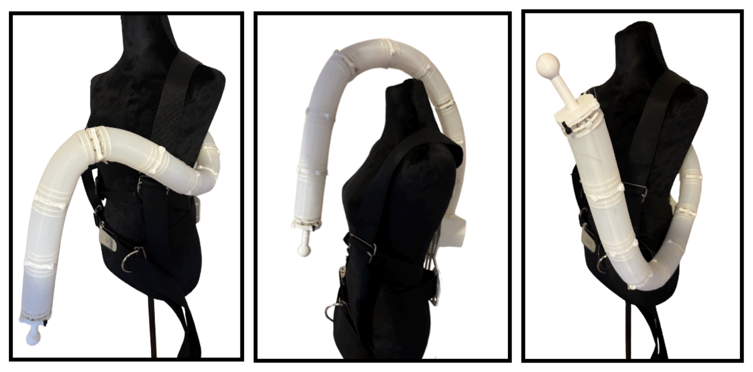
Harness with Backplate

- Includes two shoulder straps, a chest strap, and waist strap.
- PLA printed backplate attached to a nylon webbed harness

Attachment of Control Unit

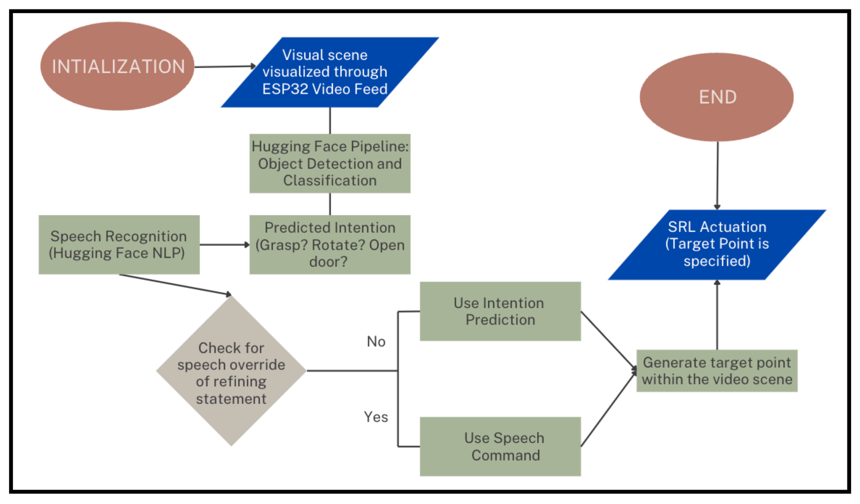
- 12, 360° servo motors with a 20kg payload placed in series
- Raspberry Pi as the main microcontroller with 48 AA Batteries

Arm Installation



- Body constructed with platinum-catalyzed silicone elastomer (Ecoflex 00-30)
- Full system weighs 14.73 pounds

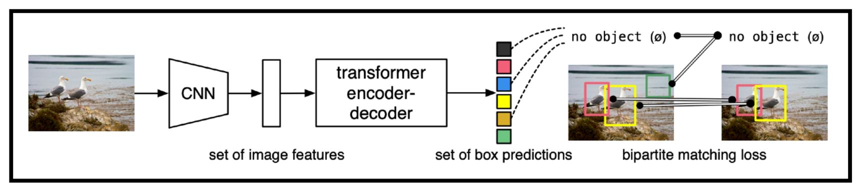
Development of Intention Prediction and Speech Actuation

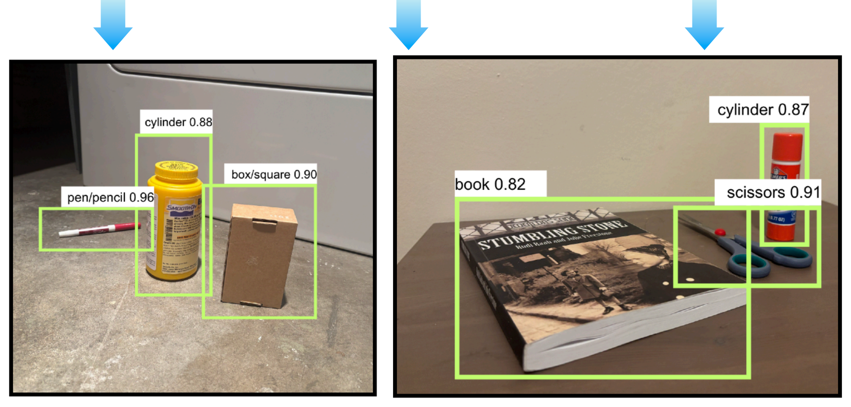


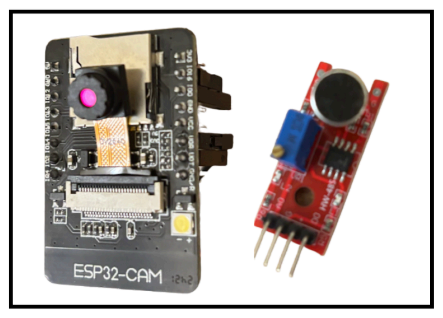
Control Algorithm Decision Flowchart

The system first uses the object detection and intention prediction pipeline then refers to speech commands, either overriding or providing specificity to a specific action.

DETR (DEtection TRansformer) combines a standard CNN with a transformer architecture







ESP32 Camera Module and Speech Module

Detection Word List

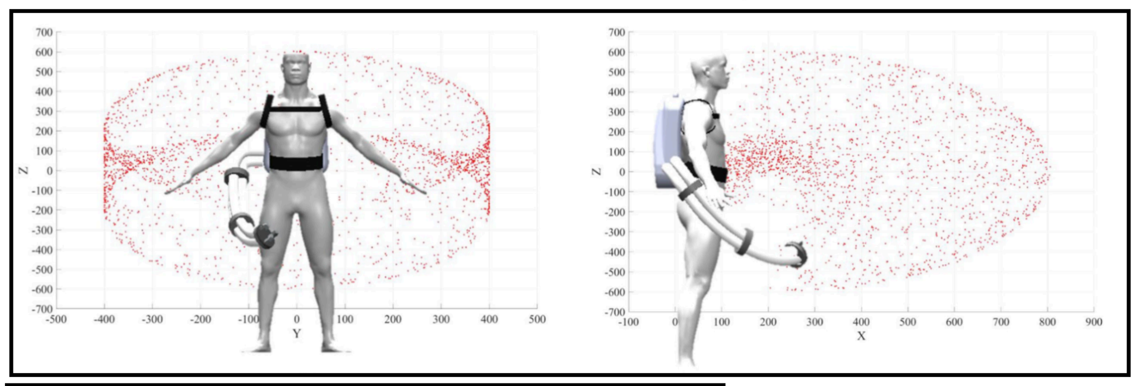
- Left
- Right
- Grab
- Door
- Hold
- Point
- Up
- Down
- Carry
- Twist
- Over
- Circle
- Square
- Front
- Back
- Handle
- Push
- (#) Degrees

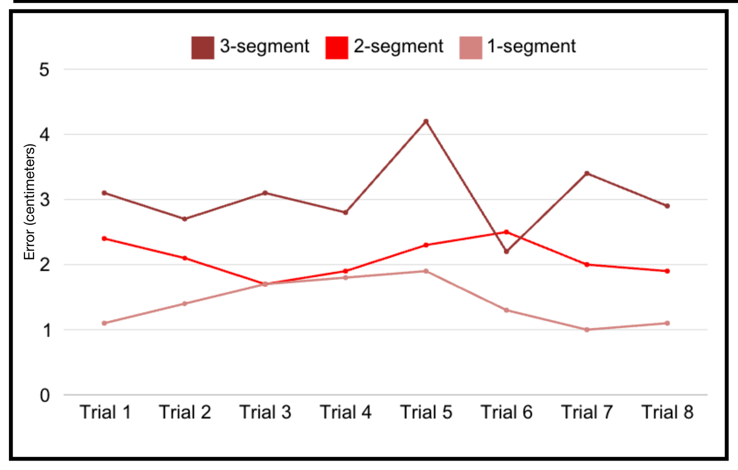
Results

Soft Continuum Arm

Point mapping around human surrogate body with motor calibration

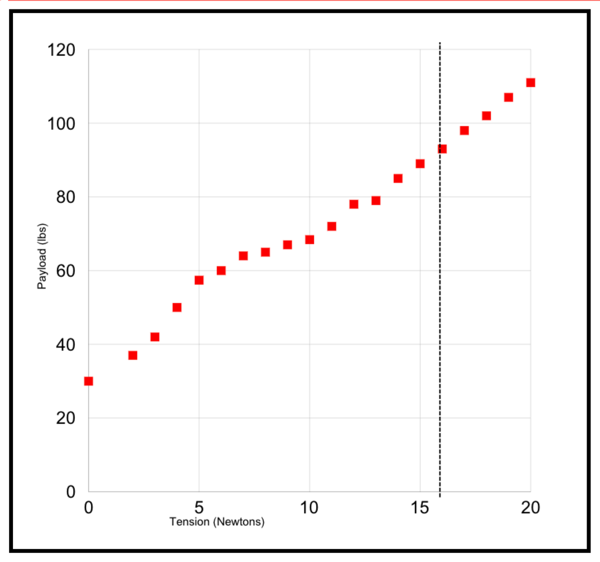
A 32% increase compared to the average human arm





Point error over 8 trials for each module: Returning an average of 2.2cm for point completion (3% error) for the end effector of the entire arm. Each movement was completed with a latency of 0.03 seconds after the cosserat model's actuation command.

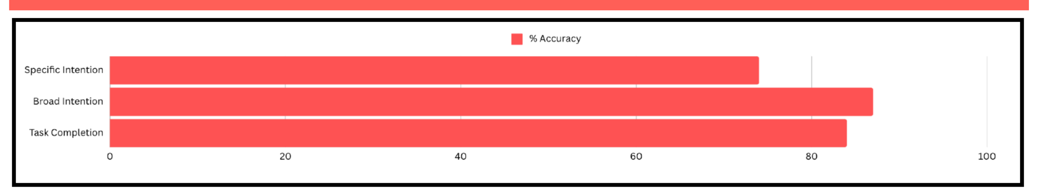
System Characteristics



Graphed payload of the arm over averaged tension in the primary tendon: Returning a maximum payload of 92.4lbs with 157 Newtons of tension. This was tested compared to the overall weight of the system, which is 16.1lbs

The full system with materials costed $247

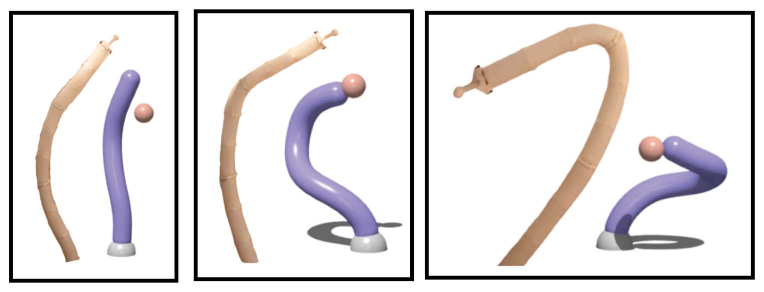
Control Algorithm



74% success rate for detection of specific intention, 87% success rate for detection of broad intention, 84% success rate in task completion

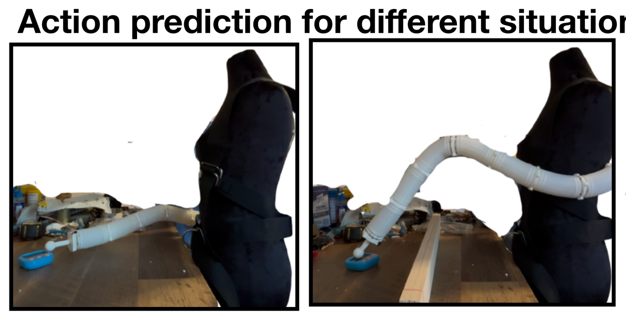
System Testing

Supernumerary robotic arm reaching for randomized points its corresponding cosserat path



- Tested the continuum arm for 45 randomized points over 30 minutes
- Calibration of motor encoders was started with choosing a constant origin point and calculating movement distances based on the change in angle of each motor rotation.
- Testing of angle variation and rotation was based on specific movement patterns and procedures
- Experimentation was conducted in a controlled environment with randomized object placements.

Action prediction for different situations with speech commands



- Touching Object, "Touch" Speech Command. This movement goes around the right of the body.
- Object avoidance, No speech Command. Goes around the left side of the body for curl efficiency.

Applications

- One major application is in **industrial and labor assistance**, where SRLs can help factory workers perform repetitive tasks without fatigue or assist construction workers by holding tools or materials, reducing the need for extra personnel. Similarly, in **first response and disaster relief**, SRLs could help firefighters manage heavy equipment or assist in search and rescue operations by clearing debris while keeping hands free for critical tasks.
- Beyond specialized fields, everyday applications include assisting individuals with mobility impairments, enabling them to perform tasks independently. Even for the general public, SRLs could enhance multitasking, such as carrying groceries while opening a door, improving convenience in daily life.
- SRLs also have promising applications in **space exploration and extreme environments**, where astronauts could use extra limbs to manage repairs and experiments in microgravity. In underwater exploration, robotic limbs could assist divers in handling delicate equipment or interacting with marine environments without compromising mobility.

Future Work

Human-Robot Interaction

- Expanding testing to include real-world environments and human participants, giving insight into system vulnerabilities and deficiencies
- Implementing a human-centered interface with feedback from the system, such as notifications of intention readiness and system alerts
- Accounting for human movements in physically demanding scenarios within the system's own movements and prediction.

Miniaturization and Power Distribution

- In the future, miniaturization of components and the development of efficient power systems would increase portability and comfort.
- Making the control unit smaller and more compact for the arm to rest on top of.

Cognitive Load

- Integrating machine learning algorithms could allow the limb to predict user intent more accurately, reducing the cognitive load required for operation.
- Further exploration of sensor fusion, combining muscle signals, eye tracking, and voice commands, could enhance the intuitiveness.

Conclusions

- The development and implementation of a novel soft, tendon-actuated continuum arm with dual-layer control has profound implications for advancing the field of wearable robotics, particularly supernumerary robotic limbs (SRLs).
- By enabling users to perform tasks previously deemed impossible, this SRL system has the potential to improve quality of life, enhance workplace efficiency, and empower individuals with disabilities—revolutionizing human-robot collaboration and redefine the boundaries of human physicality.
- The results highlight the effectiveness of continuum-based motion planning for reaching tasks and speech-driven commands for action selection, proving that supernumerary limbs can operate efficiently in dynamic environments.

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