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Non-invasive Feedback for Prosthetic Arms: A Conceptual Design of a Wearable Haptic Armband

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***Abstract*—One of the main challenges users of prosthetic hands face is the lack of haptic feedback, which can make it difficult for them to accurately perceive the shape, texture, and other characteristics of objects they are touching, resulting in heavy reliance on visual feedback. This can limit the user's ability to manipulate objects and interact with their environment effectively. In this research, we present a conceptual design of a mechanotactile haptic armband that has five fingers, each with two segments to provide different haptic profiles. The goal of this device is to provide haptic feedback to users of prosthetic hands, allowing them to experience a sense of touch and to more accurately perceive the shape, texture, and other characteristics of objects they are touching. To control the haptic armband, we have developed a control technique based on fuzzy logic, which maps the force sensed from a soft sensor to a force applied to the armband. Our results show that the haptic armband has the potential to improve the functionality and performance of prosthetic arms, enabling users to interact with their environment.**

***Index Terms*—Haptic Feedback, Mechanotactile, Prosthetic Hands, Prostheses, Fuzzy logic**

I. INTRODUCTION

The human hand can be considered to be a dexterous manipulator whose control relies on sensory information from touch and sight. Humans can identify the texture, shape, weight, temperature, force, and pressure of objects or surfaces with which the hand makes contact or handles [1]. Thus, it is possible to perform complex handling tasks without visual cues. In contrast, controlling most prosthetic hands is almost completely reliant on visual feedback due to the lack of tactile feedback [2]. This makes controlling the prosthetic hand a cognitively taxing process much unlike the hand it is replacing [2] [3]. As a result, prosthetic hands with no feedback are largely thought of as being hindrances, leading to high rejection rates by upper limb amputees [2] [4]. To solve this problem, sensory feedback must be available from the prosthetic hand and displayed in an intuitive way that allows the user to control the prosthetic hand as naturally as possible [3] [5]. Recently, two main approaches to solving the haptic feedback problem exist, invasive feedback and non-invasive feedback approaches [2] [6].

The invasive feedback approach attempts to integrate an artificial limb into the central nervous system or directly feedback sensation via the remaining nerves [7]. Accessing the central nervous system or the remaining nerves requires surgery [2] which may need to be performed multiple times. With invasive methods, it is possible to evoke sensation from the lost limb with the fingers being clearly distinguishable [8] and multiple sensory modalities being felt [8]. Re-innervated skin can be stimulated with non-invasive methods [9] [10]. Whilst invasive approaches promise to one day completely replace a lost limb with an artificial one, the main problems will be the cost and accessibility to the surgery and specialists [2].

The non-invasive approach seeks to provide feedback to patients using other sensing modalities or by stimulating the human skin [1] [3] [6]. Sensory substitution techniques are often non-intuitive and are susceptible to interference [3]. Stimulating the cutaneous surface of the skin is the most preferred approach and forms the basis of non-invasive feedback methods [6]. Modality matching is key for achieving more intuitive cutaneous non-invasive feedback [6]. If a force/pressure is sensed in the prosthetic hand and a force/pressure is felt by the user, this is modality-matched feedback [3] [5].

Vibrotactile feedback is the most explored and implemented non-invasive feedback method [3] [6]. Vibrotactile systems boast low size and power consumption, whilst providing a highly variable output [3]. Vibrotactile feedback has been used for force [11], texture [12], slippage [13] and proprioception [14] feedback. However, this mode of feedback is not very intuitive due to lack of modality matching. Electrotactile stimulation can potentially provide similar signals to that of the lost limb [15], but has the drawback of producing an unpleasant sensation especially when used over long periods and generating interference with electromyography signals [16].

Mechanotactile feedback methods can easily achieve modality-matched feedback making it a more intuitive and easier-to-interpret form of stimulation [6]. Mechanotactile systems provide one or more of the following modes of stimulation: skin stretch [17] [18] [19], compression/squeezing

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[17] [20], pushing/indenting [5], [21] and pressing [22]. Skin stretch achieves modality-matched feedback for proprioception feedback relating to finger and wrist orientation and movement [17]. Compression, pushing, and pressing achieve modality-matched feedback for force/pressure feedback and contact feedback [22]. Mechanotactile systems also provide a good platform for creating hybrid systems and have been combined with vibrotactile systems [23] to provide multiple modalities and channels of feedback. However, mechanotactile feedback devices are much larger, heavier and less power efficient compared to vibrotactile and electrotactile systems [2] [3] [24].

In this paper, we propose a mechanotactile feedback device that is smaller than the typical mechanotactile devices and is capable of five-channel force/pressure feedback, aimed at force/pressure feedback for handling tasks where grip force and contact detection are essential. We are concerned with providing a feedback solution that is practical and can be used in daily life as an attachment for different prosthetic and robot hands. Presented are the conceptual idea, working principle, CAD model of the device, controller design and our solution for tactile sensation. We also present simulation and experimental results obtained.

II. CONCEPTUAL DESIGN

A. Conceptual Idea and Objectives

The concept of our non-invasive wearable haptic armband is to allow patients to have a kind of secondary robotic hand, similar in design to the prosthetic one being controlled, as a feedback device (haptic armband). The armband would be positioned on the corresponding upper arm, allowing for the direct transference of sensory feedback to the user. The aim of this design is to enhance the user's ability to visualize and understand the actions performed by the primary prosthetic/robotic hand. By grabbing, handling, or touching objects with the primary hand, the armband would provide the corresponding sensation on the upper arm, thus providing a more intuitive and immersive experience for the user. The wearable haptic armband is proposed to have five individually actuated fingers arranged to form a robotic hand grabbing the user's upper arm.

B. Design Constraints

We limit our design to tactile sensation relating to touch, force and pressure. This feedback is ideal for grabbing, grasping, and handling tasks [22] [17]. In addition, we impose a size constraint of 3cm maximum vertical protrusion at any point. This is done to have the device as compact as possible. The minimal detectable force and maximum allowable force were determined from experimental data in the literature [5] [17] [20] and our own preliminary experimental analysis. From this we derived the following constraints and requirements:

- Minimal detectable force is 0.2N [20] [5].
- Maximum required force is 10N [5]. This coincides with our preliminary tests.
- Maximum required vertical indentation is limited to 5mm.

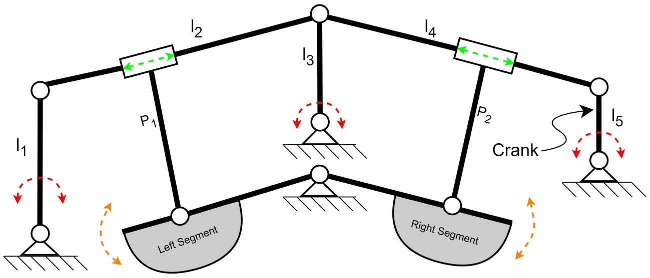

Fig. 1. Feedback mechanism for single finger

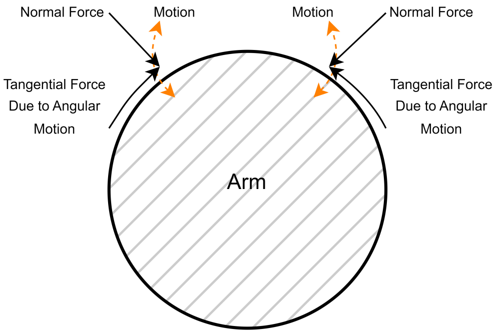

Fig. 2. Working principle for single finger feedback

C. Mechanism Design and Kinematic Model

Our proposed design consists of two segments per 'feedback finger' which make contact with the skin on the upper arm. The motion of the segments is controlled by two parallel connected 4-bar mechanisms sharing a common link l_3. On each coupler (l_2 and l_4) there is a slot where a slider and a pusher transfer motion to the segments as shown in Fig. 1. When the crank rotates clockwise, the segments are pushed into the skin. When the crank rotates anti-clockwise, the segments are lifted from the skin. Therefore, there are two stimulation sources per feedback finger. The slots in the pushers (shown in Fig. 3.) are for stability and do not constrain the motion.

D. Working Principle and Haptic Stimulation

The two segments provide two types (modalities) of stimulation to the skin as shown in Fig. 2. The first is to apply normal forces/pressures at the surface of the skin and the second is tangential forces which pinch and stretch the skin. The skin pinching and stretching are less pronounced than the force/pressure feedback and thus are a secondary mode of stimulation.

E. Single Finger Design

The feedback segments are of similar shape and size to that of human finger segments. And the motion generated is also similar to the motion of the human finger as it grabs round an object. Fig. 3. shows the setup for the thumb.

F. The Whole Haptic Armband Design

The complete haptic armband consists of two rigid semi-circular shaped platforms on which the actuators and mechanisms are mounted and two elastic regions which connect the two platforms as shown in Fig. 4. One platform contains the four fingers and the other the thumb. With this setup, the device can wrap around the arm as if it was a human hand. The elastic part allows the device to conform to the different contours of the arm giving full contact for the feedback fingers.

G. Design Process

Based on the literature and our conceptual idea, simplified working models were developed. An optimal model was then selected based on the following criteria [1] [25]:

- Size - with a main focus on the vertical protrusion from the lowest point to the highest point.
- Weight - should be as low as possible. Below 500g is acceptable [17].
- Wearability - the ease with which the device can be put on or removed [2] [17].
- Portability - a function of the size and weight [2].
- Actuation - power supply requirements, power delivery and size and weight [2].
- Stimulation type - ideally, the device can deliver more than one type of stimulation at a time, from the same actuated motion [1].

A CAD model of the optimal solution was then designed, simulated, analyzed, and modified in an iterative design process. The first iteration of the optimal model is shown in Fig. 5. This design required multiple springs to maintain the contact as shown and after simulating in ADAMS, we found this to be unstable and replaced the spring-loaded follower with a slot system requiring no springs as shown earlier in Fig. 3. The model was again simulated in ADAMS and the motion refined by tuning the link lengths until the final design shown in Figures 3 and 4 was reached. Then we selected materials based on manufacturing methods, ergonomic, and strength requirements. The model was then tested in ANSYS Workbench using static structural analysis. Areas of high-stress concentration, large deformations, colliding surfaces, and interferences were identified and modified in the design. Fig. 5. shows some of the identified colliding surfaces. We then optimized the input-to-output relationship between the sensor input and actuator movement, using MATLAB and an Adams model with real-time sensor input through an Arduino Uno in I/O mode.

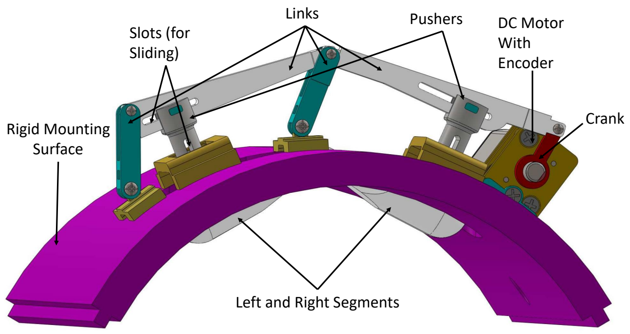

Fig. 3. Thumb assembly (single finger design)

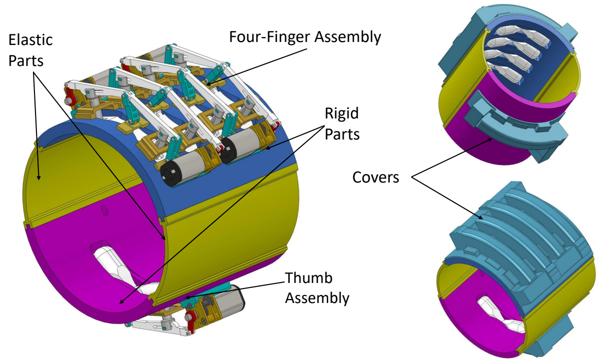

Fig. 4. The whole Haptic Armband

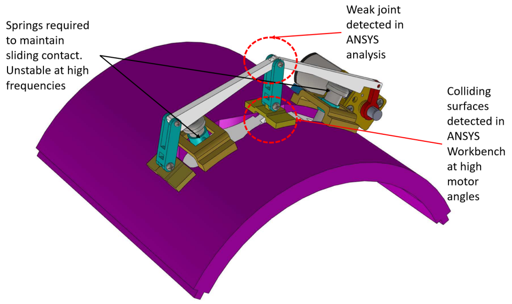

Fig. 5. Early iteration of the design

H. Tactile Sensing

To obtain tactile sensation from the prosthetic/robotic hand, we use a 5-channel feedback system with each finger being a feedback channel. We use EeonTex Conductive Fabric [26] to create the tactile sensor. The fabric produces a drop resistance when: a compressive force/pressure is applied, stretched, squeezed or twisted and, vibrated. Compressive forces and pressures cause a drop in resistance which can be detected with a Potentiometer or Wheatstone bridge setup as shown in Fig. 6. In addition, the material can be layered to change the sensitivity and range of forces/pressures that can be detected. However, the signal from the sensor is noisy and needed to be filtered to use for tactile sensation. This is discussed in the next subsection. In the setup shown in Fig. 6., each fingertip is covered with a piece of the sensor sandwiched between two wires and connected in series with a 1k ohm resistor to form

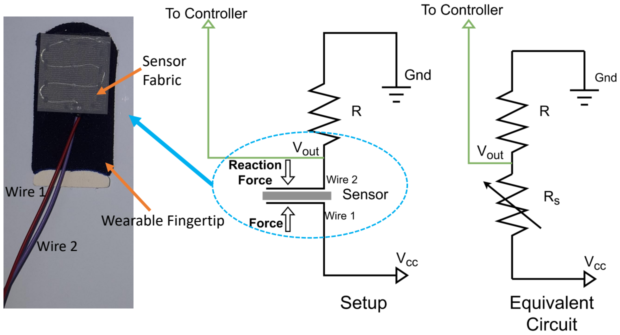

Fig. 6. Sensor setup

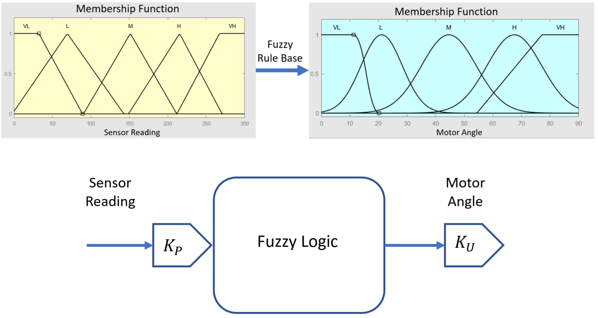

Fig. 8. Fuzzy Logic membership functions and schematic diagram

a Potentiometer. The output is taken as the voltage change across the resistor measured in bits instead of ohms:

$$V_{out} = \frac{R}{(R_s + R)} * V_{cc}$$

The sensor setup is used with both a Bebionic prosthetic hand and a human hand to collect data when the hand: grabs, grasps, squeezes and touches different objects while measuring the change in resistance produced.

I. Control Design

The controller receives input from the tactile sensors and outputs a control signal to move the actuators to the required position, as shown in Fig. 7. To determine the appropriate control action, the signal must be filtered and any sudden spikes should be removed. We decided not to use filters that modify the sensor signal as it is rich in data that may be useful for other applications for example slippage delectation. Initially, we implement bang-bang control which has five levels. Whenever the error passes set thresholds, control action is taken. However, this approach resulted in sharp control action when moving between the levels and this is greatly affected by the inertia of the driving mechanism which will resist sudden control. This problem can be solved by Fuzzy Logic Control which can eliminate the noise and allows for control action between the levels hence there is no sudden control action but instead a smoother control.

J. Fuzzy Logic Controller

The fuzzy rule base has five input rules mapped to five output rules. The inputs are the sensor readings and the outputs are the required motor angles. Fig. 8 shows the fuzzy logic controller and membership functions. The membership functions were tuned to obtain a fast response to both static and dynamic input and the levels were determined from the sensor characteristics.

III. RESULTS AND DISCUSSION

A. Real-Time Simulation with Sensor Input

Using differently tuned fuzzy logic controllers and the sensor, we simulated a real-time ADAMS model of the feedback device. The block diagram is shown in Fig. 9. We observed the responsiveness of the model to varying inputs from the sensor readings during tasks with the hand. The results are promising and the controller handled noise and disturbances well.

B. Simulation Results with Real-Time Sensor Input During Handling Tasks

The sensor was wired up to an Arduino Uno in input/output (I/O) mode and the signal passed into a Simulink model where it was logged and input into the designed controllers. The controller output then controlled an ADAMS model of the haptic armband. In the first experiment, the sensor was worn on a single finger and the finger was moved around without contacting any surfaces or objects. This experiment is used to verify that the controller can smooth out the noise (signal drops) produced when there are sudden movements.

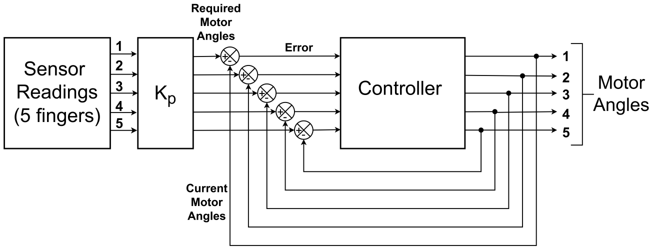

Fig. 7. Block diagram of the overall system

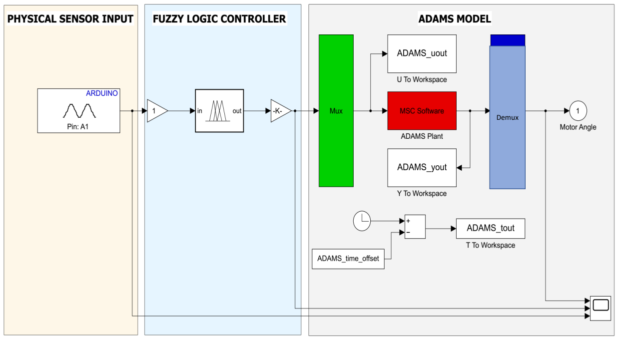

Fig. 9. Simulink simulation with physical sensor input for one finger

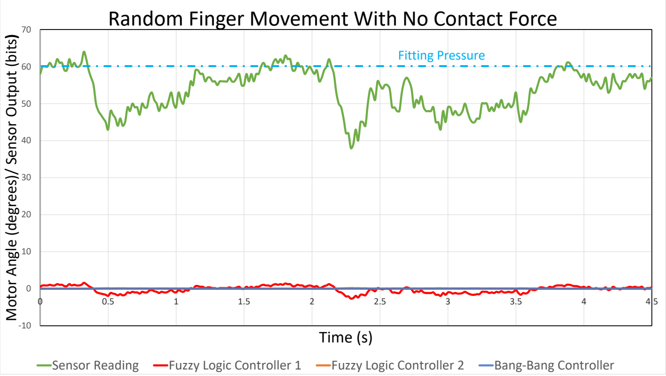

Fig. 10. Sensor and Controller response to random finger motion with no contact

The results are shown in Fig. 10. The drops in the signal correspond to the instances when the finger is moving. Note that the bang-bang controller and 'Fuzzy Logic Controller 2' coincide at 0 output. The fitting pressure indicated is the small constant contact pressure required to keep the sensor material and wires in constant contact.

In the second experiments, object handling tasks that correspond to situations a user will experience in daily life were performed. In Figures 11 and 12, a water bottle was grabbed and then moved, using a tight grip. In Figures 13 and 14, the water bottle was grabbed and released with varying force and speed. The fuzzy logic controller was able to respond to the rapidly increasing force by producing a greater motor angle than with a constant force of the same magnitude. The bang-bang controller was slower since it can move only one level at a time and is not sensitive to the rate of change of the input.

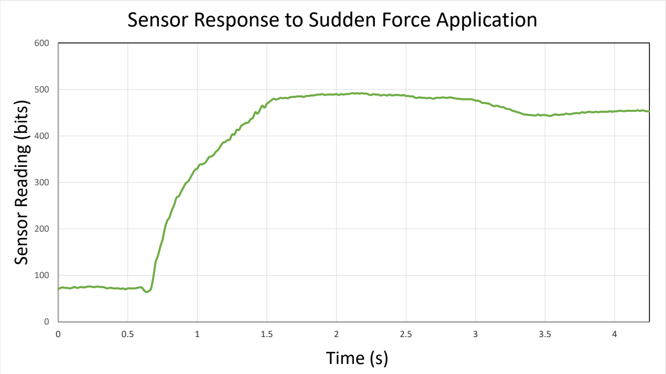

Fig. 11. Sensor response to sudden force application during grabbing task

C. Stimulation Analysis

As the motor angle increases, the segments make deeper indentations in the skin. Fig. 15. shows the how the surface area of the segments making contact with the skin increases with the motor angle. The blue area represents the skin's surface level. Thus the device should be able to provide varying and distinguishable changes in the stimulation with a changing input.

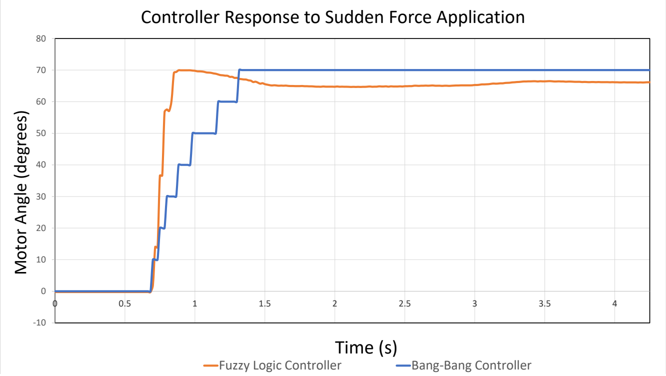

Fig. 12. Controller Response to sudden force application during grabbing task

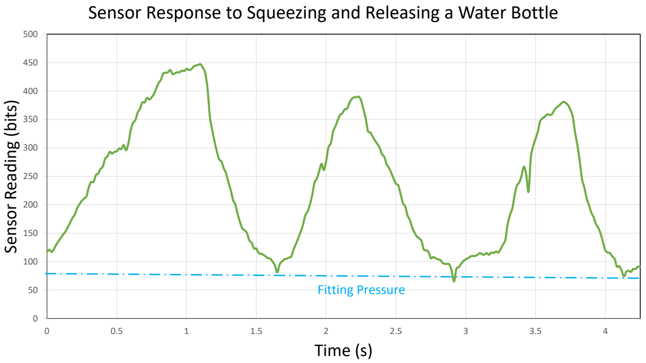

Fig. 13. Sensor Response to squeezing and releasing a water bottle

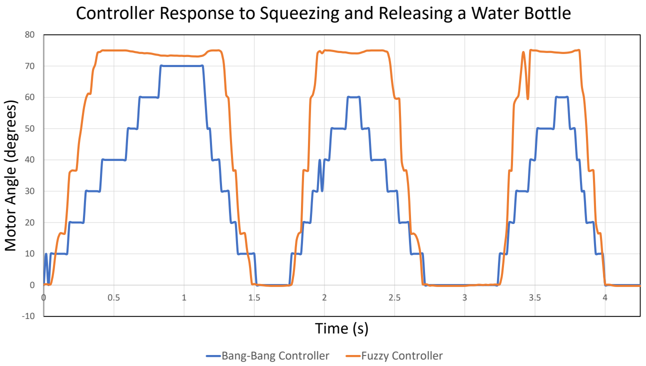

Fig. 14. Controller Response to squeezing and releasing a water bottle

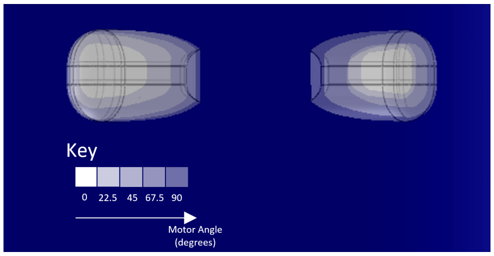

Fig. 15. Change of contact surface with motor movement

IV. CONCLUSIONS AND FUTURE WORKS

To make the feedback as intuitive as possible, we designed a haptic armband based on a conceptual idea that makes visualizing the feedback and translating it into the actual physical understanding of the prosthetic/robotic hand's state clear. When worn by the user, it should feel like a hand grabbing the user's upper arm. One of the concerns with having five feedback channels is that it might be difficult to distinguish between adjacent stimuli. To solve this we desynchronized the motion of the left and right segments making up the feedback for each finger. In addition, the arrangement of the different fingers is alternating so that the adjacent fingers can be distinguished by their motions. Our proposed haptic armband can generate both static and dynamic force/pressure feedback. The estimated weight of the whole haptic armband including the motors and batteries is less than 350g, obtained from CAD models with the selected materials.

To sense tactile information from the prosthetic/robotic hand, we developed wearable textile-based sensors that are worn over the fingertips. The sensors detect force/pressure and produce a change in resistance. We implement a fuzzy logic controller to eliminate the noise in the sensor readings and map sensor input to corresponding motor rotation.

Future works will center around the production and testing of a physical prototype of the proposed device which will be used to further optimize the proposed device based on real-world testing. Additionally, the responsiveness of the skin on the upper arm to multiple simultaneous feedback needs to be investigated as it forms the premise of our feedback solution. Although the upper arm has been successfully used for feedback [17], the proposed stimulation method requires validation with real-world testing.

REFERENCES

[1] T. A. Kern, *Engineering haptic devices*. Springer, 2009.

[2] M. N. Nemah, C. Y. Low, O. H. Aldulaymi, P. Ong, A. A. Qasim *et al.*, "A review of non-invasive haptic feedback stimulation techniques for upper extremity prostheses," *International Journal of Integrated Engineering*, vol. 11, no. 1, 2019.

[3] B. Stephens-Fripp, G. Alici, and R. Mutlu, "A review of non-invasive sensory feedback methods for transradial prosthetic hands," *IEEE Access*, vol. 6, pp. 6878–6899, 2018.

[4] E. J. Wolf, T. H. Cruz, A. A. Emondi, N. B. Langhals, S. Naufel, G. C. Peng, B. W. Schulz, and M. Wolfson, "Advanced technologies for intuitive control and sensation of prosthetics," *Biomedical Engineering Letters*, vol. 10, no. 1, pp. 119–128, 2020.

[5] K. Kim, J. E. Colgate, J. J. Santos-Munné, A. Makhlin, and M. A. Peshkin, "On the design of miniature haptic devices for upper extremity prosthetics," *IEEE/ASME Transactions On Mechatronics*, vol. 15, no. 1, pp. 27–39, 2009.

[6] C. Antfolk, M. D'alonzo, B. Rosén, G. Lundborg, F. Sebelius, and C. Cipriani, "Sensory feedback in upper limb prosthetics," *Expert review of medical devices*, vol. 10, no. 1, pp. 45–54, 2013.

[7] D. J. Tyler, "Restoring the human touch: Prosthetics imbued with haptics give their wearers fine motor control and a sense of connection," *IEEE Spectrum*, vol. 53, no. 5, pp. 28–33, 2016.

[8] X. Liu, G. Chai, H. Qu, and N. Lan, "A sensory feedback system for prosthetic hand based on evoked tactile sensation," in *2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*. IEEE, 2015, pp. 2493–2496.

[9] K. Kim and J. E. Colgate, "Haptic feedback enhances grip force control of semg-controlled prosthetic hands in targeted reinnervation amputees," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 20, no. 6, pp. 798–805, 2012.

[10] C. Antfolk, M. D'Alonzo, M. Controzzi, G. Lundborg, B. Rosen, F. Sebelius, and C. Cipriani, "Artificial redirection of sensation from prosthetic fingers to the phantom hand map on transradial amputees: vibrotactile versus mechanotactile sensory feedback," *IEEE transactions on neural systems and rehabilitation engineering*, vol. 21, no. 1, pp. 112–120, 2012.

[11] T. Rosenbaum-Chou, W. Daly, R. Austin, P. Chaubey, and D. A. Boone, "Development and real world use of a vibratory haptic feedback system for upper-limb prosthetic users," *JPO: Journal of Prosthetics and Orthotics*, vol. 28, no. 4, pp. 136–144, 2016.

[12] S. Okamoto, M. Konyo, S. Saga, and S. Tadokoro, "Detectability and perceptual consequences of delayed feedback in a vibrotactile texture display," *IEEE Transactions on Haptics*, vol. 2, no. 2, pp. 73–84, 2009.

[13] M. Aboseria, F. Clemente, L. F. Engels, and C. Cipriani, "Discrete vibro-tactile feedback prevents object slippage in hand prostheses more intuitively than other modalities," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 26, no. 8, pp. 1577–1584, 2018.

[14] E. I. Germany, E. J. Pino, and P. E. Aqueveque, "Myoelectric intuitive control and transcutaneous electrical stimulation of the forearm for vibrotactile sensation feedback applied to a 3d printed prosthetic hand," in *2016 38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*. IEEE, 2016, pp. 5046–5050.

[15] M. Peruzzini, M. Germani, and M. Mengoni, "Electro-tactile device for texture simulation," in *Proceedings of 2012 IEEE/ASME 8th IEEE/ASME International Conference on Mechatronic and Embedded Systems and Applications*. IEEE, 2012, pp. 178–183.

[16] C. Hartmann, S. Došen, S. Amsuess, and D. Farina, "Closed-loop control of myoelectric prostheses with electrotactile feedback: influence of stimulation artifact and blanking," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 23, no. 5, pp. 807–816, 2014.

[17] S. Casini, M. Morvidoni, M. Bianchi, M. Catalano, G. Grioli, and A. Bicchi, "Design and realization of the cuff-clenching upper-limb force feedback wearable device for distributed mechano-tactile stimulation of normal and tangential skin forces," in *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2015, pp. 1186–1193.

[18] K. Bark, J. Wheeler, P. Shull, J. Savall, and M. Cutkosky, "Rotational skin stretch feedback: A wearable haptic display for motion," *IEEE Transactions on Haptics*, vol. 3, no. 3, pp. 166–176, 2010.

[19] F. Chinello, C. Pacchierotti, J. Bimbo, N. G. Tsagarakis, and D. Prattichizzo, "Design and evaluation of a wearable skin stretch device for haptic guidance," *IEEE Robotics and Automation Letters*, vol. 3, no. 1, pp. 524–531, 2017.

[20] C. Antfolk, A. Björkman, S.-O. Frank, F. Sebelius, G. Lundborg, and B. Rosen, "Sensory feedback from a prosthetic hand based on air-mediated pressure from the hand to the forearm skin," *Journal of rehabilitation medicine*, vol. 44, no. 8, p. 702, 2012.

[21] D. D. Damian, M. Ludersdorfer, Y. Kim, A. H. Arieta, R. Pfeifer, and A. M. Okamura, "Wearable haptic device for cutaneous force and slip speed display," in *2012 IEEE International Conference on Robotics and Automation*. IEEE, 2012, pp. 1038–1043.

[22] C. Antfolk, C. Balkenius, G. Lundborg, B. Rosén, and F. Sebelius, "Design and technical construction of a tactile display for sensory feedback in a hand prosthesis system," *Biomedical engineering online*, vol. 9, no. 1, pp. 1–9, 2010.

[23] M. A. Abd, J. Ingicco, D. T. Hutchinson, E. Tognoli, and E. D. Engeberg, "Multichannel haptic feedback unlocks prosthetic hand dexterity," *Scientific reports*, vol. 12, no. 1, pp. 1–17, 2022.

[24] B. T. Nghiem, I. C. Sando, R. B. Gillespie, B. L. McLaughlin, G. J. Gerling, N. B. Langhals, M. G. Urbanchek, and P. S. Cederna, "Providing a sense of touch to prosthetic hands," *Plastic and reconstructive surgery*, vol. 135, no. 6, pp. 1652–1663, 2015.

[25] L. A. Jones and N. B. Sarter, "Tactile displays: Guidance for their design and application," *Human factors*, vol. 50, no. 1, pp. 90–111, 2008.

[26] SparkFunElectronics. (2017) Eeontex conductive fabric. [Online]. Available: https://www.sparkfun.com/products/14110