DEVELOPMENT OF THE HANDI HAND: AN INEXPENSIVE, MULTI-ARTICULATING, SENSORIZED HAND FOR MACHINE LEARNING RESEARCH IN MYOELECTRIC CONTROL

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ABSTRACT

Machine learning (ML) has been applied in both research and clinical settings to make myoelectric prostheses more functional and more intuitive to use. ML techniques for myoelectric control require information about the environment a control system occupies in order to make useful control decisions or predictions about a user's desired control outcomes. Despite demonstrated increases in myoelectric control performance with the inclusion of additional information about users and their environments, the sensors in commercial prostheses are limited, and typically do not provide diverse channels of contextual information to their respective control systems. Additional sensor information is crucial to demonstrating and evaluating the full potential of next-generation ML control systems. With this in mind, a novel, cost-effective research prosthesis was designed to provide real-time sensory information for ML-based myoelectric control. This device is able to report fingertip forces on independently controlled fingers, angular position for individual finger joints, and visual information about the hand's environment via a USB webcam integrated in the palm. Using 3D printing, the device was prototyped at a cost of less than $800 CAD. This work therefore contributes a new platform by which groups can conduct ML research on prostheses, and allows researchers to develop new ML approaches with ample access to contextual information about prosthesis movement, prosthesis-environment interactions, and local changes to the environment surrounding the prosthesis. By providing an inexpensive, highly sensorized prosthetic hand, this work helps mitigate the cost of purchasing and retrofitting commercial prostheses with new sensors; it is therefore also expected to support related research into methods for sensory feedback from prostheses to users.

INTRODUCTION

Advanced bionic limbs such as the Modular Prosthetic Limb (Johns Hopkins University, Laurel MD, US), Bebionic (RSL Steeper, Leeds, UK), or i-Limb (Touch Bionics, Mansfield MA, US) demonstrate increasing similarity to biological limbs in terms of their functionality and their kinematic capabilities. However, as with many systems that have more degrees of freedom than available control signals, the in-practice dexterity of myoelectric prostheses is limited by the effort required to control them—non-intuitive control and lack of accessible functionality are two of the main reasons for the low acceptance rate of upper-limb myoelectric prostheses [1–3]. Machine learning in the form of pattern recognition, regression learning, and reinforcement learning have all been demonstrated as ways to potentially reduce the control burden on users while increasing the functionality of prosthetic devices [2].

Previous work has shown that increasing the sensor space provided to a pattern recognition system—for example, adding accelerometers to provide a sense of residual limb position—have a noticeable effect on the ability of the control system to make correct classifications in different situations [4]. More generally, it is natural to expect that machine learning predictions, and therefore control decisions, may be improved by increasing the control system's awareness of the environment it is acting in—that is, by giving the learning system increased sensory feedback. Sensory feedback has also been shown to improve a user's control over their prosthesis [5]. Commercially available prostheses however, either lack the ability to gather sensory information, or lack a purposely-designed means of transferring detailed information to the user or to a learning agent [6]. Further, the cost of these devices can be prohibitive in some research settings.

By improving a prosthetic control system's window into its own operation, the world around it, and the intentions of its human user, significant gains can be expected in terms of the capacity of that system to meets its user's needs in diverse and changing circumstances [2, 7]. The present work therefore contributes a novel research prosthesis—the Humanoid Anthropometric Naturally Dexterous Intelligent (HANDi) Hand—that has been designed to allow a rich stream of information to be delivered to a machine learning agent or human user.

Table 1: Design specifications for HANDi Hand.

Item	Design Specification	Achieved Spec.
Size	Full scale, anatomical proportions	Criteria met
Mass	< 500 g	256 g
Max Payload	500 g	500 g
Degrees of Freedom	Flexion/extension of each finger plus abduction/adduction of thumb	Criteria met
Degrees of Actuation	Each finger independent; thumb adduction separate from flexion	Criteria met
Sensing	Position, fingertip force, visual data	Criteria met
Interface	Compatible with Bento Arm	Criteria met
Modularity	Exist as standalone system	Criteria met
Prototype Cost	< $2500	$800
Finger Speed	Full close in < 1 s	0.43 s
Grip Force	> 4 N cylinder grip	4.2 N

DESIGN SPECIFICATIONS

The design specifications for the HANDi Hand are outlined in Table 1. The device was designed to operate either as a standalone system or in conjunction with the Bento Arm—a 3D printed upper-limb prosthesis previously developed at the University of Alberta for myoelectric training and research [8]. As such, the size was specified to be 1:1 scale with anatomical proportions similar to the Bento Arm. In order to not detract significantly from the Bento Arm's total payload capacity, the mass of the device was restricted to less than 500 g. Most tasks performed with the device for machine learning trials and many tasks of daily living do not require large payloads; therefore the hand was specified to support a maximum payload of 500g in a cylinder grip (equivalent to holding a 500 mL water-bottle). This equates to approximately a 4 N cylinder grip.

To ensure natural dexterity of the device, all natural degrees of freedom of a human hand were included in the design, with the exception of lateral finger movement. These degrees of freedom were excluded due to the increased level of complexity they would introduce. Many commercially available hands underactuate the fingers, causing fingers to flex and extend in concert with one another to simplify control. Since the goal of the research is to make control intuitive without loss of dexterity, it was decided that each finger should be independently actuated, and thumb rotation should be independent of thumb flexion.

Key sensory abilities to include were force and position sensing for each of the fingers, as these would provide similar information to what a biological hand would naturally supply. To allow exploration of non-physiological sensory capabilities, the capacity for visual feedback was also included via an in-palm camera.

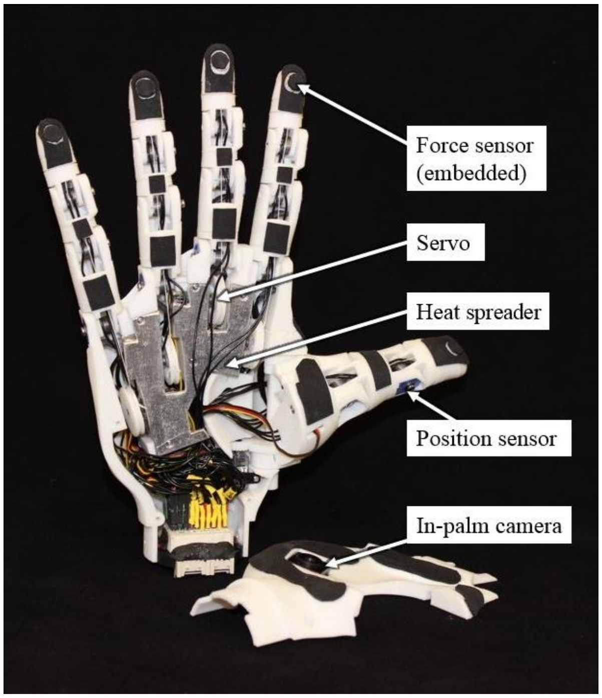

Figure 1: Assembled HANDi Hand prototype with six servo motors installed and palm cover removed.

In order to make the device accessible to other research groups and facilitate rapid design iterations, the cost of the device was specified to be less than $2500.

MECHANICAL DESIGN

All parts of the device were modelled in 3D design software and printed on a Replicator 2 desktop 3D printer (MakerBot Industries, LLC, Brooklyn NY, US). As a starting point, the finger was modelled after a previously designed open-source finger from the InMoov project [9]. Modifications were made to this finger to allow for the introduction of position sensors, force sensors, and an altered extension scheme. The thumb was then modelled using the same hinge mechanism with modified proportions. In order to maintain anthropometric dimensions, the size of the fingers, thumb, and carpus were modelled to match a 50th percentile male. Each of the fingers are identical in length, modelled after the proportions of the ring-finger, in order to simplify design iterations. Anthropometric considerations of individual finger length are compensated for by unique positioning of each finger on the carpus. The assembled prototype, with palm cover plate removed to show interior workings, is shown in Figure 1.

Flexion of each finger is actuated by the rotation of a Hitec HS 35-HD servo motor. These motors were chosen because their small size allows all components to fit within the palm of the hand, as per the modularity requirement.

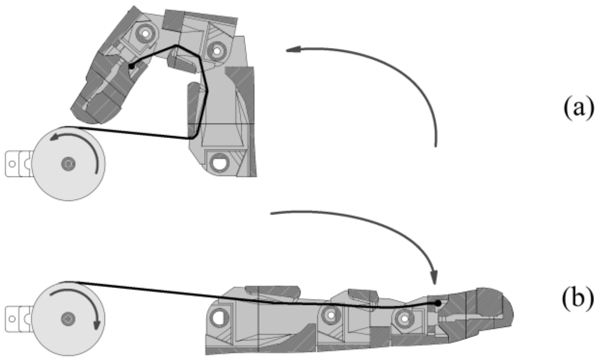

Figure 2: Cutaway view of finger actuation mechanism showing (a) flexion by winding up on the servo spool and (b) extension by releasing the spool allowing torsion springs at each joint to extend the finger.

As the servo horn turns, a nylon thread attached at the tip of the finger spools around the servo horn causing flexion as seen in Figure 2. As the servo rotates in the opposite direction, the thread unspools and a torsion spring at each joint causes extension. This mechanism allows the finger to wrap around objects using the distal joints.

During long periods of continuous use, the temperature of the servomotors can reach temperatures high enough (~85˚C) to cause the 3D printed plastic to soften. To combat this, a plate was machined from 2 mm thick aluminium and acts as both a heat spreader and cover plate keeping the servos in place. The wrist of the hand is designed to mount directly to the Bento Arm, and can also be mounted to a separate stand for independent use.

ELECTRICAL DESIGN

Control of the servos and aggregation of sensor signals is accomplished on an Arduino Mega (Arduino LLC, Italy), chosen due to its high number of analog pins. Servo position is encoded using velocity control over the Arduino's PWM outputs. To negate voltage drop on sensor readings, the servos are powered separately from the rest of the system. The servos can be controlled by any analog signal: for example, joystick or myoelectric signals. When used with the Bento Arm, the Arduino takes control signals from and sends sensor data to a BeagleBone Black Rev2, which operates on the Robot Operating System (ROS).

Force sensing at each fingertip is accomplished by use of a force sensitive resistor (FSR). Change in pressure normal to the FSR causes a proportional change in its resistivity and therefore voltage drop, which is measured through a voltage divider circuit. The FSRs are embedded within the fingertip to ensure consistent orientation regardless of change in the environment, and are actuated by pressing on a column that runs through the fingertip normal to the FSR (Figure 3).

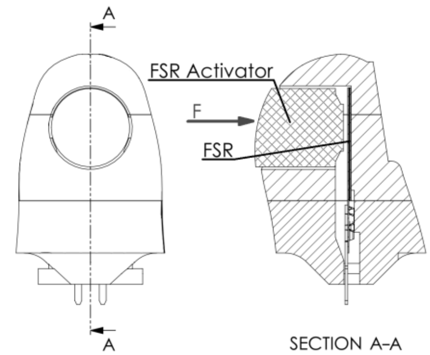

Figure 3: Section view showing FSR setup. Force F displaces the FSR activator column, thereby applying force to the embedded FSR.

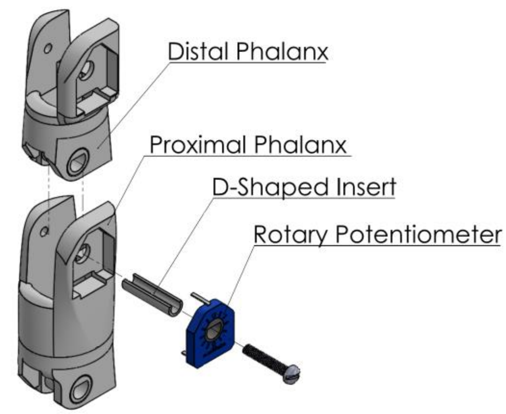

Figure 4: Exploded view of one finger joint showing potentiometer setup. The D-shaped insert rotates with the distal phalanx, turning the hub of the potentiometer. The potentiometer is fixed relative to the proximal phalanx.

The angle between each joint is measured by a MuRata SV series rotary potentiometer (MuRata Manufacturing Co. Ltd., Kyoto, JP). A D-shaped plastic insert rotates with the more distal phalanx while the body of the potentiometer is fixed to the more proximal phalanx as pictured in Figure 4. Due to limitations in the number of analog signal pins available on the control board, the most distal joints in each finger as well as the intermediate joints in the little and ring fingers are not equipped with potentiometers at this time; allowances have been made for their addition in the future.

An in-palm USB webcam was included by dissecting a Logitech QuickCam Pro (Logitech, Newark CA, US), and appropriating the functional components for use in the hand. The camera's circuit board and lens is attached to a custom mount on the palm cover, and the original USB cable passes directly out of the hand and into the computer, bypassing the control board.

PROTOTYPE CHARACTERISTICS

Force output from the fingertips was measured using an external load cell (LCM703-5, OMEGA, Laval QB, CA, calibrated to an accuracy of 0.02 N, resolution 0.003 N) placed at the fingertip approximately 77 mm from the metacarpophalangeal (MCP) joint. The average force output was 0.81 N, s = 0.05 N. The grip force was measured using the same load cells mounted inside an 80 mm diameter cylinder. The hand provides a radial cylinder grip force of 4.21 N, s = 0.33 N. In practice, the hand was able to support a 500 g water-bottle without slipping.

Embedding the FSR within the fingertip limits the perception of force to a binary indication of the presence of force. The sensor reading increases with greater forces, but the differences were not found to be significant enough to establish a relationship. There is a measurable difference between the FSR voltage at no force applied and at forces greater than 0.20 N, indicating that the sensors provide a reliable indicator of whether or not force is applied.

Repeatability of the finger movement was measured using the built-in potentiometers. The potentiometers (accuracy 1.2°, resolution 0.35°) were calibrated within the finger using a goniometer. In both open and closed positions, the angle of joints with potentiometers were analysed, and found to be repeatable with a standard deviation of less than 3.4° across all measured finger joints.

Material cost of the prototype including all hardware, sensors, and servos was less than $800 CAD, not including shipping charges. Fabrication and assembly costs are also not included in this appraisal.

FUTURE WORK & CONCLUSIONS

In order to make the HANDi Hand a fully modular system, control and signal acquisition should be integrated into the cavity of the palm rather than existing as it does now on an external Arduino. This will require custom PCB design, which will increase the cost of manufacturing and may create a barrier to other groups wishing to build their own version. Integration of control into the hand will however reduce the amount of cables required, making the hand more accessible for wearable use. Further improvements to the current prototype will involve more sensing capabilities: load sensing, temperature sensing, additional cameras, and more comprehensive position sensing are near-term considerations. Also being considered is the inclusion of an LCD display screen for visual feedback to the user.

In conclusion, the HANDi Hand is a functional prototype with force, position, and visual sensory capabilities that can be constructed for less than $800. The sensory information it provides will enable machine learning control systems to more accurately represent the hand's environment and interactions. Increased sensory information to a machine learning myoelectric control system is expected to enable contextually appropriate control decisions on the part of the controller, and more appropriate natural myoelectric control for end users.

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