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Oguz Yetkin, Simranjit Ahluwalia, Dinithi Silva, Isioma Kasi-Okonye, Rachael Volker, Joshua R. Baptist, Dan O. Popa, "An extremely lightweight fingernail worn prosthetic interface device," Proc. SPIE 9859, Sensors for Next-Generation Robotics III, 98590J (17 May 2016); doi: 10.1117/12.2235567



Event: SPIE Commercial + Scientific Sensing and Imaging, 2016, Baltimore, Maryland, United States

### An extremely lightweight fingernail worn prosthetic interface device

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#### ABSTRACT

Upper limb prosthetics are currently operated using several electromyography sensors mounted on an amputee's residual limb. In order for any prosthetic driving interface to be widely adopted, it needs to be responsive, lightweight, and out of the way when not being used. In this paper we discuss the possibility of replacing such electrodes with fingernail based optical sensor systems mounted on the sound limb. We present a prototype device that can detect pinch gestures and communicate with the prosthetic system. The device detects the relative position of fingers to each other by measuring light transmitted via tissue. Applications are not limited to prosthetic control but can be extended to other human-machine interfaces.

**Keywords:** Prosthetic, gesture sensor, wearable hand tracking, wearable electronics, light based gesture detection, EMG, finger nail, ubiquitous computing

#### **1. INTRODUCTION**

Controlling a robotic prosthetic device remains a challenge for many amputees despite advances in robotic technology. Ultimately, the ability to control the prosthetic device is limited by the biological signals available. Almost all powered prosthetic systems to date have relied on electromyogram (EMG) sensors. In our previous work, we explored alternatives, such as the use of a mirroring glove<sup>1</sup> as well as a lightweight pinch gesture glove utilizing skin conductance<sup>2</sup>. Pinch gestures<sup>3</sup> are intuitive gestures, which can be performed by touching the fingers of the hand to other fingers or the palm of the hand. Pinch gesture tracking gloves are commercially available<sup>4</sup> but require the use of a glove on the healthy hand, which ultimately limits manipulation ability with that hand. These systems typically use conductive fabric and the completion of a circuit by touching various parts of the glove together. Other gesture tracking systems require the use of a camera or other 3D tracking system <sup>5</sup>. Kim et al.<sup>4</sup> have proposed a gesture tracker using a wrist worn camera that obviates the need for a glove, but introduces occlusion errors. Nonetheless, they have demonstrated the ability to control various devices by performing both simple and complex gestures with the hand. Other types of gesture systems such as the Myo<sup>6</sup> and the GEST<sup>7</sup> (https://gest.co) rely on EMG bracelets or accelerometers linked to a lightweight bracelet/glove system. The Myo is an EMG based bracelet which also uses accelerometers to allow the performance of various gestures defined by the manufacturer to allow for the control of various types of applications such as mp3 players, slide presentation software (PowerPoint), or computer games. The Myo device has also been used to control a prosthetic device <sup>8</sup>. The GEST <sup>7</sup> system uses accelerometers tethered to a bracelet worn by each fingernail to recognize various gestures. Mascaro et al<sup>9</sup> have created a fingernail mounted system which works by using miniature LEDs and photodiodes in order to detect color changes in the fingernails in response to pressure applied to the fingertips.

In this paper, we discuss a novel sensor interface for the healthy hand consisting of an extremely lightweight fingernail worn gesture tracking system relying on red/infrared light transmission through the fingers which can be entirely unterhered and unnoticed by the user until needed. The basis of our device is a compact; nail worn light transmitter-receiver pair that can detect contact events. We describe our initial prototype consisting of fingernail sensors interfaced to a microcontroller, demonstrating that the proposed methodology can ultimately lead to an extremely low cost and completely unterhered device. Even though the proof of concept prototype presented is tethered to a microcontroller, the system we propose does not have any inherent need to be tethered and the

Sensors for Next-Generation Robotics III, edited by Dan Popa, Muthu B. J. Wijesundara, Proc. of SPIE Vol. 9859, 98590J · © 2016 SPIE · CCC code: 0277-786X/16/\$18 · doi: 10.1117/12.2235567

transmitters on the fingernails can be built to be untethered without requiring any communication with the rest of the system except the light they emit/detect.

#### 2. MATERIALS & METHODS

Fingernail mounted sensor holders for an LED and photodiode were modeled in SolidWorks and 3D printed using a filament extruder based printer. A high powered 639 nm LED and a broad-spectrum photodiode were friction fit into the sensor holder. Both the LED and the sensor on each sensor holder were soldered to thin wires. The wires were connected via DuPont connectors to a wrist worn microcontroller board. The microcontroller board was constructed out of a Velcro<sup>™</sup> wristband, an Arduino Genuino microcontroller board, and a custom Arduino shield with circuitry to drive the LEDs and read the input from the photodiodes as depicted in Figure 1. The prototype system created using one thumb sensor and two fingernail sensors is depicted in Figure 2.



Figure 1: Sensor holder design and implementation



Figure 2 Proof of Concept system with a wrist-worn microcontroller (top) and three pinch gestures (bottom)

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Certain wavelengths of light travel through tissue<sup>10</sup>. The phenomenon is exploited by the use of a "light guide" when the two fingers touch, thus allowing light directed at a fingernail to be detected at a sensor aimed at the thumbnail. This phenomenon is illustrated in Figure 3. The graph on the left side of the figure represents signal transmission picked up by a detector when the fingers are touching and the graph on the right represents the signal detected from the same detector when the fingers are close but not touching.



Figure 3 Light detected on a fingernail after traversing through two fingers in physical contact (left), and light detected on the same fingernail after traversing through two fingers with a small air gap between them (right)

For this paper, the system was used to detect and classify finger touch events. The detection algorithm is broken into detection windows of fixed length (*window\_duration*), for instance 200 ms. During each detection window, the LED on each non-thumb digit is pulsed for a very short time (e.g., 5 ms) which we denote as *pulse\_duration*. The LED on each non-thumb digit is assigned a characteristic response time, denoted as *response1*, *response2*, *response3*, *response4* (for instance 25 ms, 40 ms, 57 ms, and 75 ms,) These times are chosen to be smaller than *window\_duration*, , but larger than *pulse\_duration*. Simultaneously, the microcontroller reads the light intensity on the photodiode and looks for peak intensities corresponding to the response times (response1, response2, etc.). Detection of such a peak is counted as a touch event. While there is always a chance of a spurious activation of the sensor, reducing the *pulse\_duration* helps prevent this since the system detects the time of the brightest signal within *window\_duration*. Therefore, a smaller *pulse\_duration/window\_duration* ratio is preferred. In order to make the system even more robust against noise, a *detection\_window* variable is defined, which will require a number of successive detection events (e.g., 3) to occur before the system will report a completed gesture. Although light intensity decays exponentially with distance, according to Beer-Lambert law<sup>11</sup>, enhancement of light transmission by the two fingers coming into contact provided a reliable touch signal in Figure 3.

#### **3. EXPERIMENTS PERFORMED**

In order to characterize the performance of our system, one healthy 40 year old male volunteer with no dexterity problems wore the system on his non-dominant hand as depicted in Figure 4. Informed consent was obtained from the volunteer in accordance with the IRB protocol covering our experiment.



Figure 4 Performance experiment setup depicting two gestures performed during timing experiments

In addition to the circuitry required for the fingernail sensors, two LEDs (yellow and blue) were mounted on the wrist of the subject. These LEDs were flashed in 1.2 second successive intervals to indicate one of three possible actions as depicted in Table 1. A total of 10 touch events were recorded along with the time data and a value indicating which gesture was being prompted.

Action	Response
0 (No LED)	No gesture
1 (Yellow LED)	Touch pad of index finger to thumbnail
2 (Blue LED)	Touch pad of middle finger to thumbnail

 Table 1 Gesture Prompt Protocol

In order to pick optimal design parameters for the system, light attenuation from one volunteer was characterized. The wavelength of the LED being used in the system (30-01SURC, Everlight Americas Inc., Carrolton, TX) was measured by a USB4000 spectrophotometer (Ocean Optics, Dunedin, FL), and LED intensity measured by a PM100D optical power and energy meter (THORLAB, Newton, NJ). Two additional measurements were taken with one and two fingers (with one stacked on top of the other) in the optical path of the energy meter. Furthermore, the distance from the index fingernail to the finger pad and the total distance from the index fingernail to the thumb fingernail while performing a pinch gesture were measured with digital calipers.

#### 4. EXPERIMENTAL RESULTS

The data from the gesture performance experiment were analyzed by a MATLAB script in order to characterize the time between the visual prompt and response detected by the system. The system compares the idealized responses from the system based on the prompt given to the user (0, 1, or 2, corresponding to no gesture, gesture 1, or gesture 2), and the response detected by the system (0, 1, or 2). The details of this process are illustrated in Figure 5 where the red trace represents the "ground truth" data, which is recorded along with the detection data during the course of the performance experiment. The vertical axis of the graph represents the current state which is prompted or detected. A state of "0" indicates that the user was instructed to perform no gesture. A state of "1" indicates that the LED prompting for "gesture 1" was on and a state of of "2" indicates that the LED prompting for "gesture 2" was on. A MATLAB script called extract\_response\_delay was created to automatically detect events on the rising edge of either signal, while ignoring brief transient detection errors.





This MATLAB script identified touch events based on the rising edge of the detected gesture signal, while ignoring transient misclassifications such as the one identified as "Detection Noise" in the figure. The program calculated the time difference between the touch prompt and the detection of the touch event to be  $0.681 \pm 0.15$  seconds (mean delay). This is a combination of the gesture performance delay inherent in human perception and the gesture detection delay. A total 8 events were correctly identified, after visual prompt was displayed. In this scheme, there are three event categories: Event 0 (no touch), Event 1 (index finger touch), Event 2 (middle finger touch). This process is illustrated in (Figure 5) and (Figure 6). While the start of each event was identified correctly, some noise can be seen in the last three events.



Figure 6 Gesture performance experiment results.

The LED's wavelength was found to be 639 nanometers (this agrees with the specification by the manufacturer), and power was measured to be 1248.3 microwatts. Since the sensor size and LED distance remained the same throughout the experiment, the measured power is assumed to be proportional to the LED intensity.

The intensity of light was measured after passing through one and two fingers. The distance of both one and two finger was measured in cm. The depth of the index finger was measured to be 1.182 cm, and the total path traveled by light passing through both the index finger and the thumb was measured to be 2.003 cm. Two separate values of the attenuation coefficient  $\mu$  were calculated according to the Beer-Lambert law (Equation 1) and averaged.

$$I = I_o e^{-\mu x}$$

(1)

In Equation 1,  $I_o$  represents the incident light on the system, and x the distance light travels through the system. The parameter  $\mu_1$  represents the attenuation coefficient through the index finger,  $\mu_2$  the attenuation coefficient of the index finger-thumb system, and  $\mu_{average}$  is the average of both. The parameters were found to be 3.27, 3.46, and 3.37 cm<sup>-1</sup>, respectively. The optical extinction coefficients of various human tissues are well characterized and are not expected to vary for a given type of tissue. Cheong et al.<sup>12</sup> give a comprehensive review of various extinction coefficients of human tissue. Light going from one finger to another may, however, undergo additional losses not described by the Beer-Lambert law. Factors that influence the performance of the system are skin color and the thickness of the finger. However, due to properties of optics it is determined that skin conditions, such as sweat, do not affect the performance of the system. For the design of this system, the important factor is that the light directed at a fingernail be detectable at the thumbnail when the two fingers are in contact, as illustrated previously in Figure 3.

#### 5. DISCUSSION

The gesture performance experiment indicates that the response detection time was around 0.6 seconds. While this is outside the accepted range of human stimulus to visual stimuli (typically around 0.25s), several factors must be kept in mind: 1) The device and the detection algorithms are still in their preliminary stages, and streaming data to a PC from the device induces a significant amount of delay to the microcontroller. 2) This experiment was performed on the non-dominant hand, using a "thumbnail gesture" in which the user touches the top of the thumbnail with one of the finger pads. This is a somewhat unnatural pose and may not facilitate the fastest device performance.

Tissue Characterization resulted in slightly different values of the attenuation coefficient  $\mu$  for one finger and for the system formed by the index finger and the thumb. While the system relies on the relatively easier passage of light from one finger to the other during the performance of the pinch gesture, some loss of light at the finger-finger boundary was expected. While we have not modeled the behavior of light at the boundary between the fingers, the purpose of averaging the two attenuation coefficients was to ensure that the Beer-Lambert law still gave a useful approximation of the light attenuation properties of the two finger system in which light is transmitted from the fingernail ot the thumbnail as seen in (Figure 7, top left).

The nature of the attenuation coefficient leads to an important design consideration for the system. There is 27 times less light available at the thumbnail if the light has passed through both fingers as opposed to only one. It is, therefore, easier to implement a "thumbnail gesture" in which the user wears the fingernail mounted LEDs and performs gestures by touching the pads of any one of the four fingers to the thumbnail (Figure 6, bottom left).



Figure 7 Tissue characterization experiment results

#### 6. CONCLUSION AND FUTURE WORK

Even without any further improvement, we believe the device to be sufficiently advanced for our intended purpose, which is the control of prosthetic devices. Four gestures can very easily be mapped onto four prosthetic device configurations such as "open" and three grasp positions such as lateral grasp or pinch grasp. Many more gestures are easily available including, but not limited to: chord gestures in which multiple fingers can touch the thumb, gestures where touching the pad of the thumb has a different meaning than touching the thumbnail. In fact, using a variant of the system discussed here in which LEDs and photodiodes are present on both the fingernail facing side

and the outside facing side of the device, readily available gestures go up to 12 from four (e.g., finger pad touches thumb pad, finger pad touches thumb nail, thumb pad touches finger nail).

Time based gestures (such as hold, long hold, etc.) are very common in EMG based prosthetic control and can be adapted to our system. In addition, concepts can be borrowed from PC interfacing such as double-click and triple-click. Using "double tap" and "triple tap" would also increase the value of the system by making more gestures readily available.

It should be noted that the primary use of this system in prosthetic control will be to select a grasp pattern on the prosthetic hand using the healthy limb when such a pattern is needed. In order to avoid activating the prosthetic hand when not needed, a gesture to turn the prosthetic control functionality on and off will be needed. This can be easily accomplished by using a gesture which is not normally performed such as the "double tap" or "triple tap" patterns discussed above in order to activate or deactivate the prosthetic mapping functionality.

Another concern which will need to be addressed in a field-deployable untethered version of the system is that of power. We intend to initially power the fingernail mounted sensors with small batteries, such as those used for hearing aids or watches. Battery life on the untethered sensors can be extended in various ways. One of the ways under development in our laboratory is the use of a "light interrogator" system in which the thumbnail sensor (which is expected to be connected to a larger rechargeable battery) and all fingernails have both a photodiode and an LED. In this system, the thumbnail based system sends out an "interrogation pulse" which causes the fingernail based sensors to respond only upon detecting it, ensuring that no extraneous light flashes will be performed by the untethered fingernail based sensors.

Work is also under way in implementing a system which addresses the problems of power consumption, noise, and untethering by flashing LEDs on each fingernail based device at different frequencies. In this embodiment of the device, the thumbnail based sensor would be connected to a device performing a Fast Fourier Transform (FFT). Unlike the time based detection system used in the initial prototype, a bright light pulse is not needed. This cuts down on both the size of the LEDs used and the power consumed by them. This approach can be further combined with the light interrogator system described above to ensure that the fingernail sensor batteries do not need to be replaced often.

Other future improvements of the device include a miniaturized implementation using a custom microcontroller board instead of the Arduino based system, adding wireless capability to the thumb based receiver, and amplifying the signal from the photodiode in order to reduce LED size and power. Other system parameters such as the exact wavelength of light to use, and the placement of sensors will need to be optimized in order to minimize the effects of fingers making contact at various orientations to each other. The final embodiment of the device and finger attachment method will also have to be decided upon.

We believe our system can increase the quality of life of amputees by providing a ubiquitous and "always on" interface to their prosthetic devices while staying out of their way when not needed. The same reasons may also make this device useful outside the amputee community, in areas such as virtual reality, teleoperation, and industrial/medical scenarios in which devices or software need to be controlled by a human without touching external buttons or screens.

#### 6. ACKNOWLEDGEMENTS

This work was supported by National Science Foundation NRI Grant #IIS-1208623. The authors would also like to thank Dr. Digant Dave and Dr. Subrata Batabyal for their help in LED characterization, as well as Ms. Karen Kitchen and Ms. Asenath Kitchen for their prototyping assistance.

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