2017 First IEEE International Conference on Robotic Computing

Design Guidelines for Sensor Locations on 3D Printed Prosthetic Hands

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***Abstract*—Recently, the advent of 3D printers has enabled people to produce a lot of inexpensive and obtainable prosthetics. In addition to that, various sensors have also been developed and used to give intelligent functions to the prosthetics. However, there may be cases where the number of sensors attached to the prosthetics should be limited due to cost, limited space, or power issues as the number of sensors increase. Therefore, in this paper, we provide a design guideline that could be used to determine the ideal sensor locations, particularly when the number of sensors is limited by finding out the locations of the high contact areas where the prosthetic hand touches the object. To this end, we experiment with a popular prosthetic hand made using a 3D printer. The prosthetic hand with gloves is used to touch two different objects that are covered with black ink, and the area of ink transferred onto the gloves is measured by image processing. Experiments are conducted ten times on the same object to obtain statistical results, and as a result, we show the most contact areas with the objects and present the guidelines.**

***Keywords*—Prosthetics; 3D printing technology; sensor locations; design guidelines; sensor layer**

I. INTRODUCTION

The estimated prevalence of limb loss will reach 2 million by the year of 2020 in the United States [1]. From the statistical result [1], the most frequent cause of limb loss is by vascular disease (54%), which is a non-congenital, followed by trauma (45%). Those who lost their limb due to non-congenital causes suffer from significant difficulties in everyday life, in which difficulties come from the difference between the experience in memory before the loss and the current circumstance after the loss. For this cause, various medical and research organizations, and commercial companies such as Johns Hopkins University Applied Physics Laboratory, DEKA Research and Development Corporation, Touch Bionics, and bebionics are focusing on the prosthetic limb development, especially the upper limb for those who lost their whole arm or partial loss [2]. The level of the upper limb loss is divided into eight different levels [3]. More than 60% of loss is below the wrist, which is the loss of a hand. The human hand is a very complex yet powerful tool in daily life. The hand has 21 DOF (Degree of Freedom), and the wrist has 6 DOF. It also plays a pivotal role in the physical and social interaction. Because of the complexity of the hand, current commercially available prosthetic hands have an extremely high price. Even though with expensive materials and sophisticated actuators and sensors, they still have various limitations such as a small number of DOF and the heavy weight of the hand [4].

Figure 1: 3D printed Flex-Hand model for the handshake (Left) and object grasp (Right) experiment. A thumb angle of the hand is different because the position of the thumb changes depends on the various task.

The idea of developing low-cost prosthetics is not new, but as the 3D printing technology grows, it boosted the development of the 3D printed prosthetic hand [5]. Currently, many open source prosthetic hands are available such as Open Bionics, OpenBionics.org, and YouBionic. The biggest benefit of those 3D printed prosthetic hands is the personalization. It is very easy to reproduce the product and especially for children who suffer from the limb loss. The open source initiative such as the e-Nable community foundation provides the 3D printable data source based on the individual hand size. This foundation founded in 2013 and delivered more than 2000 hands to children in 50 countries till now in 2017 [6]. This prosthetic hand is called 'Cyborg Beast,' it is a purely mechanical device (no electronic device), and it costs only around $50. 'Flex-Hand' from Gyrobot is also popular 3D printable prosthetic hand, and it has more human-like hand design [7].

An upper limb prosthetic can be classified into two categories, the passive and active [3]. The Passive prosthetic also has two subcategories which are cosmetic and functional. The cosmetic prosthetic aims at the aesthetic situation, so when prosthetic hand users interact with people, the design of hand is substantial due to the users' desire of showing their prosthetic hand. The functional prosthetic has a specific purpose such as work and sports. The active prosthetic uses either body-powered or externally powered. Most expensive

978-1-5090-6724-4/17 $31.00 © 2017 IEEE
DOI 10.1109/IRC.2017.81

prosthetics are based on the external power, and many 3D printed prosthetic hands are cable driven by the servo motor. In this paper, we used the Flex-Hand model to conduct the proposed study due to the design aspect and this hand can be operated by the body-power or external power.

II. MOTIVATION

People use hands for social and physical interactions every day. The handshake is a good example of the social interaction, and it is the primary gesture in many cultures [8]. Also, the power of handshake is already proved by the neuroscience technology [9]. The handshake drives social interactions positively and by reversing negative impressions, and it evaluates the social interaction with partners [9]. The handshake interaction can also improve the emotional healing process of the prosthetic hand users [8]. To improve the handshake interaction for the prosthetic hand users, developing a human-like hand is essential. For developing the human-like hand, varied types of researches have been done by covering the prosthetic hand with soft materials which feel like human skin with different types of sensor arrays. The conventional sensors on the prosthetic hand are a temperature sensor and a force sensor [10] [11]. However, as the number of sensors increases, the limited area of the prosthetic hand becomes more scarce and power or cost issues rises, therefore finding the optimal number of sensors and optimal location of sensors are necessary [12].

As we grasp many things in our daily life, prosthetic hand users also want to grasp an object which they need in everyday living. Research results in grasp taxonomy are very useful to understand the human hand behavior and to develop improved prosthetic hands. The human grasp taxonomy can be classified into three classes; power, intermediate and precision [13] [14]. In this paper, we consider the power grasp of the prosthetic hand. From the statistic result in [15], 59% of the grasping object is the cylindrical object. We choose the cylindrical type object to find an optimal location of sensors for the prosthetic hands when grasping.

The main goal of this research is to present the design guidelines by finding an optimal location of sensors for the prosthetic hands when handshaking and grasping daily objects.

III. RELATED WORK

Despite the remarkable development of prosthetic hands, they are still affected by many limitations. One of the main challenges in an engineering perspective is to embed all components such as actuators, electronic devices, and sensors into the same size of the human hand, and the weight of the prosthetic hand should be light enough for users. One of the highest expectation from users in the development prosthetic hand is the 'feeling'; how people can feel from the prosthetic hand like a normal hand [16]. Current research at the Functional Neural Interface Lab at Case Western Reserve University is to restore prosthetic hand users' feeling of tactile and temperature when they touch objects. They implanted electrodes on the nerves and conducted an experiment with the volunteer from the Louis Stokes Cleveland Veterans Affairs Medical Center [17]. The first experiment was successful, and in addition to the tactile, they would like to generate sensations such as temperature, pain, and joint position.

Figure 2: A fixed Flex-Hand for handshaking (Left) and a cylindrical water bottle for object grasping (Right). For the purpose of maintaining even coverage of black ink to remain on the surface across multiple trials, a disposable latex glove was used on the Flex-Hand.

The electronic skin (E-skin) has been developed since the 1970s. The ultimate goal of this artificial skin is to create human-like sensory capabilities which have a wide multi-sensory surface. It is highly applicable for robots, medical diagnostics, and prosthetic devices [18]. Recently, an artificial skin manufactured with a stretchable silicon nanoribbon electronics for prosthetic hands and biomedical devices has been introduced [19] [20] [21]. The skin is an ultrathin single crystalline silicon nanoribbon with various types of sensors such as strain, pressure, and temperature sensor array associated with humidity sensors, electro-resistive heaters, and multi-electrode arrays [19]. Despite the advanced technology, however, due to the sensitive and complex structure, most of the sensor arrays are symmetric and evenly distributed.

A human hand has almost 17,000 tactile units under the skin and contains four different types which are two fast adapting types and two slow types, and tactile sensory units are not evenly distributed [22] [23]. The human hand is very complex, and it is not evenly coated with nerves and sensory units. As such, optimal sensor distribution and locations should be considered to develop more human-like prosthetics [12] [24]. Moreover, the energy efficiency issue arises for the use of the prosthetic hands. An adaptive grasp control has been developed to use the minimum force to grab the objects [25]. To predefine the sensor location before apply the adaptive control, the importance of the optimal number and location of sensors is significant.

IV. 3D PRINTED PROSTHETIC HAND

As we mentioned in Section I, there are many open source 3D printable prosthetic hand designs. We selected a model called 'Flex-Hand' from Gyrobot [26] because this model has the most human-like hand design and has been widely used. The finger phalanges and the palm are 3D printed with the rigid plastic, but the finger joints are made of a flexible material such as silicone.

The mechanism of the open source 3D printable prosthetic hands is similar to the aforementioned 'Cyborg Beast.' For

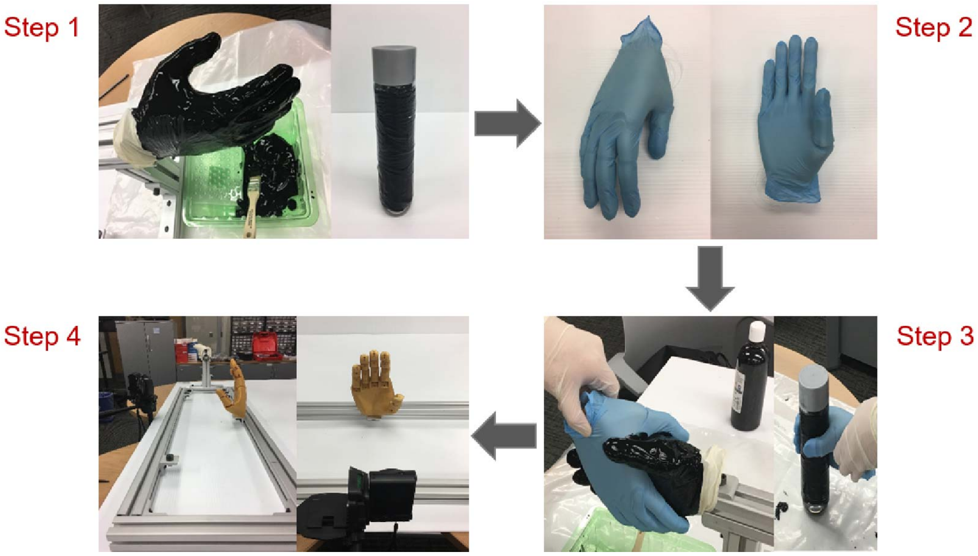


Figure 3: Experiment procedure. Step 1: Apply the black ink to the Flex-Hand and the water bottle, Step 2: Put a disposable latex glove on the Flex-Hand, Step 3: Have the Flex-Hand shake hands with the inked Flex-Hand and grasp the inked water bottle, and Step 4: Take a photo of the front view of the object.

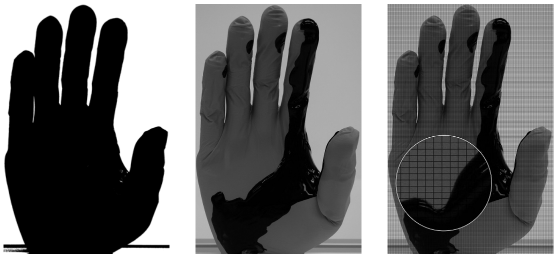
the flexion and extension movement, each finger is driven by the cable such the fishing wire. The Flex-Hand is also generating the finger movement by pulling each wire. Fig. 1 shows the 3D printed Flex-Hand for the experiment. We printed two different types of hand because the position of the thumb changes depending on the task. For the handshake experiment, the hand with 45° thumb is used, and for the grasp experiment, the hand with 90° thumb is used.

V. EXPERIMENTS

We conducted two types of experiments; i) handshaking and ii) daily object grasping. The main objective of the experiment is to find the most frequent contact area. For the handshake experiment, another 3D printed Flex-Hand model is used (Fig. 2 Left) with the assumption that it is the hand of the person who is interacting with users. For the object grasping experiment, a cylinder type bottle is used (Fig. 2 Right) since it is the common shape such as the water bottle, tumbler, or glass cup.

A. *Methodology*

The experiments were conducted with the four steps as depicted in Fig. 3. The initial step (Step 1) is to paint the object. We painted both the fixed hand for the handshake and the water bottle with the washable black paint. The second step (Step 2) is to cover the Flex-Hand with the disposable latex glove. The third step (Step 3) is to have the prosthetic hand grasp the object. When the Flex-Hand shakes hands and grasps the water bottle, the contact area is smeared with the black paint on the glove. After each handshake and grasp, we take a photo of the Flex-Hand from the front view; palm view. We repeat the step 2 to the step 4, ten times to obtain the statistically significant data. If the repainting of the object is required, we go back to the step 1 and repeat the entire process.

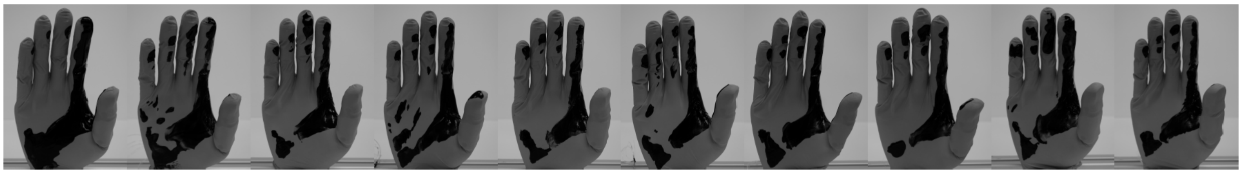


(a) binary (b) grayscale (c) grid

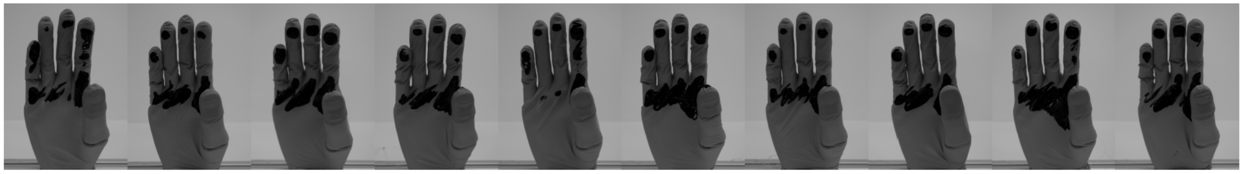
Figure 4: Photos were taken with the prosthetic hand that shook hands and grasped the object. The photos are gone through a series of processing, which includes (a) and (b) converting the color space from RGB to binary and grayscale; the former is used as prosthetic hand boundary detection, and the latter is used as the actual source of ink intensity data. Finally, (c) a grid of 200×100. These processes are presented in Algorithm 1.

B. *Image Processing*

We used MathWorks MATLAB for processing the images taken in Step 4 into intensity data and Microsoft Excel for crunching the data. In MATLAB, an image is loaded as a 3-dimensional matrix of values ranging from 0 to 255; each dimension represents red, green, blue channels. Then, the matrix went through a grayscale function, yielding a 1-dimensional matrix with the same number of rows and columns. Also, a binary—black and white—representation is created from the original image, in the same format as the grayscale one. Fig. 4 depicts each representation of the picture. After we had prepared two matrices, we segmented the image into several cells (20,000 cells in this case), which we try to get the average of paint area inside each cell. We iterated through every single pixel of both grayscale matrix and binary matrix; whenever the pixel in the binary matrix is of value 0, the pixel is considered a part of the prosthetic hand, adding



(a) Ten handshaking trials photographed and converted to grayscale



(b) Ten cylinder-grasping trials photographed and converted to grayscale

Figure 5: 10 photos taken during trials on each type of objects. The photos show that the contact areas made when the prosthetic hand was shaking hands with another hand and grasping the water bottle shown in Fig. 2.

the pixel value of the grayscale matrix into the buffer of the arithmetic mean function. When we hit the boundary of a cell, the mean function is executed, giving us an average of the paint intensity value inside the cell. After we had got 20,000 means, we gathered each of the means that belongs to a specific zone, which we divided along the shape of the hand. A summary of these step is presented in Algorithm 1.

VI. RESULTS AND GUIDELINES

In this section, we analyze the data gathered from the experiment and present the guidelines of the sensor locations on 3D printed prosthetic hands based on the analysis. We used ten different images taken with each object for image processing as shown in Fig. 5. The values (circled dots in the whisker plot) in Fig. 6 indicate the means of the hand contact with the other objects obtained with ten different images. Originally, we measured the coverage of ink as the contact intensity, so the closer, tighter, and broader the contact is, the lower the values yielded. However, to match with the nuance of the term ‘intensity,’ we inverted the value—i.e., lower values to higher values and higher values to lower values, in the domain of $0 \ldots 255$—so that the closer, the tighter contacts are represented by higher values. Both Fig. 6 and Fig. 7 are following this notion.

A. Results

Initially, we expected that the handshaking would yield a broad area (i.e., overall the entire hand covered with ink), but the actual results showed that mostly a narrow band starting from the index finger and ending at the lower left side of the palm had made contact with the other prosthetic hand. As we can see in Fig. 7 (Left), zones that belong to the index finger, lower palm, and zones connecting these two are showing higher values compared to other zones. This result indicates that the arch-like shape of the hand makes the mid-palm area to be off contact when handshaking.

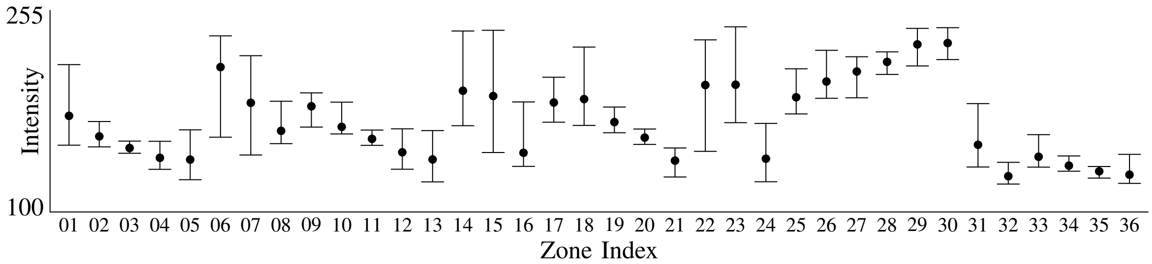
For the cylindrical object, our original prediction was that the contact would be focused on entire fingers and the upper part of the palm. The results show that we got the finger part wrong, but the palm part was correct. As shown in Fig. 7 (Right), most of the ink intensity in the result were focused on zones that are on upper palm, with a few zones on each fingertip, not entire fingers.

Algorithm 1 Image processing for analyzing images to find out the high contact area

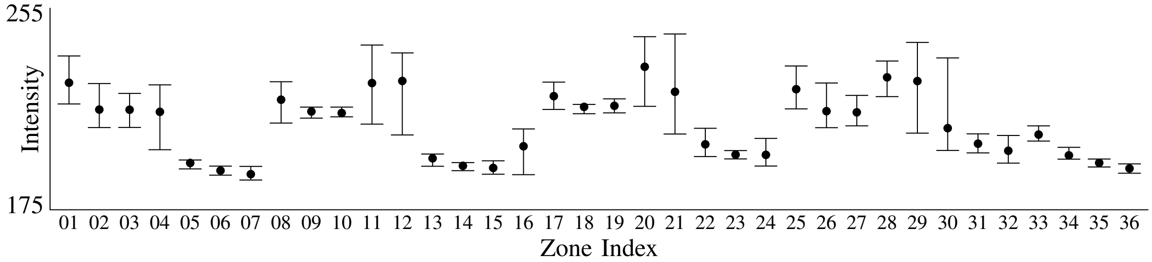
```
$P \leftarrow$ Original photo in RGB color space
$BW \leftarrow$ A black & white version of $P$
$GS \leftarrow$ A grayscale version of $P$
$AVG \leftarrow$ A blank matrix of size $200 \times 100$
$K \leftarrow {}^{\text{Height of } P}/_{200}$, the height of each cell in pixel
$L \leftarrow {}^{\text{Width of } P}/_{100}$, the width of each cell in pixel
for all the $20,000$ cells identified by $(i,\ j)$, where
        $i \leftarrow 1 \ldots 200$ and $j \leftarrow 1 \ldots 100$ do
    Define two variables: $avg\_sum$ for storing the
    sum of all eligible pixel values in $GS$ and
    $avg\_num$ for storing the number of those
    eligible pixels
    for all the pixels in a cell identified by $(m,\ n)$,
            where $m \leftarrow (K(i-1)+1) \ldots Ki$ and
            $n \leftarrow (L(j-1)+1) \ldots Lj$ do
        if the pixel $(m, n)$ of $BW$ is 0 then
            The pixel is part of the hand, so add the
            pixel $(m, n)$ of $GS$' grayscale value to
            $avg\_sum$, and increase $avg\_num$ by 1
        end if
    end for
    if $avg\_num > 0$ then
        $AVG(i, j) \leftarrow {}^{avg\_num}/_{avg\_sum}$
    end if
end for
return $AVG$
```

B. Guidelines

Based on the results and analysis above, we attempt to point important positions to focus on applying sensors on a



(a) Distribution of ink intensity upon handshaking



(b) Distribution of ink intensity upon grasping a cylinder

Figure 6: Distribution of ink intensity. The circled dots indicate the means of the hand contacts with the other objects measured from 10 repeated experiments. Higher values indicate the more contacts take place. The zone index on horizontal axis can be found in Fig. 7.

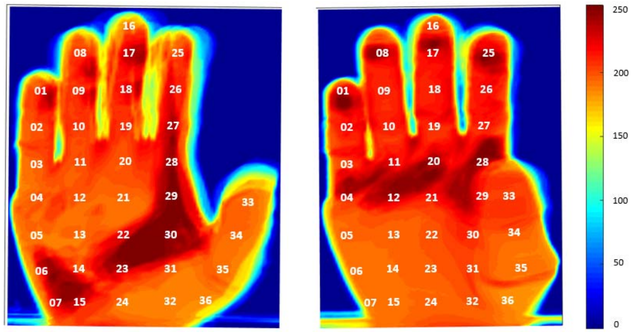


Figure 7: Ink intensity upon handshaking (Left), ink intensity upon grasping cylinder (Right). Darker red area indicates that the more contact occurs. The numbers in the images indicate the defined zones used in Fig. 6.

prosthetic hand. Assume that we are to attach two types of sensors: a contact temperature sensor and a force sensor. For both of types, the closer or tighter the contact is, the more accurate the sensor reading. Thus, under a situation where the total number of sensors is limited, care should be taken on selecting sensor positions on the hand.

Force sensors are often utilized when grasping objects, where measuring how tight the object is being grasped is crucial; too tight or too high force will break the object, and too loose or too low force will drop the object. To get a relatively accurate force readings with a limited number of sensors, one could consider putting them on Zones 28, 25, 20, 17, 12, 08, 04, and 01, in the listed order, as shown in Fig. 7.

Likewise, contact type temperature sensors can be possibly used for handshaking, or also for grasping objects. Similar to the force sensor, the contact type temperature sensor requires a tighter contact for more accurate reading. Thus, for the same reason, one could consider putting the sensors on Zones 30, 29, 28, 27, 23, 15, and 07, in the listed order, as shown in Fig. 7.

VII. Conclusion and Future Works

There are few better ways of integrating sensors on prosthetic hands, i.e. covering the entire hand with myriads of sensors, but that would require a high-level manufacturing equipment capable of doing such sophisticated assembly. Our research focuses on attaching limited numbers of sensors on an affordable 3D printed prosthetic hands, which does not rely on a complicated manufacturing process. As such, we present the guidelines of locating sensors on 3D printed prosthetic hands.

The order of zones we listed above are based on the contact area measured in ink intensity; the wider the contact happen, the more intense the ink level is, therefore giving us zones that contacts with objects the most on a prosthetic hand. Therefore, for various reasons, if to use less sensor than usual, attaching sensors in order of the rank we suggested above would be the most optimal and efficient placement.

For the future works, it is necessary to conduct an experiment on various types of objects besides the hand and cylinder, such as round objects that resemble door knob, thin and small objects that resemble keys, or more. Finding more accurate and global grasp patterns on these various objects will enhance the current outcomes by determining optimized sensor placement for many circumstances. We used only a front view figures to analyze grasp patterns. However, since all these actions are taking place in a 3D space, it is better to analyze in an alternative way. For achieving this goal, it is important to find the methods for the 3D scanning. For example, using an array of cameras placed in 360° around the prosthetic hand or using a camera specialized in 3D scanning would be a possible approach.

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