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14. ABSTRACT
We are building and evaluating a new system called *HandSight*, which is aimed at supporting activities of daily living (ADLs) for people with severe visual impairments by sensing and feeding back non-tactile information about the physical world *as it is touched*. HandSight consists of tiny cameras and micro-haptic actuators integrated into one or more fingers, computer vision algorithms to support inference and recognition, and a smartwatch for processing, power, and speech output. We have two high-level goals: first, to develop the basic building blocks of an extensible HandSight platform that will support a range of ADL applications. Second, to explore and demonstrate the potential of HandSight through three proof-of-concept applications: reading, dressing, and technology access. In the first year of funded work, we have focused largely on the first goal, including: designing and iterating on physical form factors, developing computer vision algorithms to extract attributes of the physical world and to support on-body interaction for mobile technology accessibility, and experimenting with haptic feedback options to guide the user's finger/hand.

15. SUBJECT TERMS
Blind, visually impaired, wearable computing, computer vision, vision-augmented touch, activities of daily living (ADLs), assistive technology, haptics, real-time OCR

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1. **INTRODUCTION:** Narrative that briefly (one paragraph) describes the subject, purpose and scope of the research.

Over one million US Veterans have visual impairments (VI) that affect their ability to perform activities of daily living—a number that continues to rise as the US Veteran population ages [2]. While previous research has explored combining mobile cameras and computer vision to support people with VI for at-a-distance information tasks such as navigation (*e.g.,* [1, 6, 16, 18, 31, 39]), facial recognition (*e.g.,* [10, 23, 24]), and spatial perception (*e.g.,* [19–21]), they fail to support proximal information accessed through touch. In our research, we are pursuing a fundamentally new approach: a vision-augmented touch system called *HandSight* aimed at supporting activities of daily living (ADLs) by sensing and feeding back non-tactile information about the physical world *as it is touched*. HandSight consists of tiny CMOS cameras ($1 \times 1mm^2$) and micro-haptic actuators integrated into one or more fingers, computer vision and machine learning algorithms to support fingertip-based sensing, and a smartwatch for processing, power, and speech output. Since touch is a highly attuned means of acquiring information for people with VI [12, 34], we hypothesize that collocating the camera with the touch itself will enable new and intuitive assistive applications. Imagine, for example, touching a printed page and receiving speech output while haptic cues guide your fingers along the text, touching a piece of clothing to hear suggestions for coordination, or even picking up a bell pepper and instantly recognizing that it is red or green. In the next sections, we articulate the key objectives of our work and our progress thus far.

2. **KEYWORDS:** Provide a brief list of keywords (limit to 20 words).

Blind, visually impaired, wearable computing, computer vision, vision-augmented touch, activities of daily living (ADLs), assistive technology, haptics, real-time OCR

3. **ACCOMPLISHMENTS:** The PI is reminded that the recipient organization is required to obtain prior written approval from the awarding agency Grants Officer whenever there are significant changes in the project or its direction.

What were the major goals of the project?

List the major goals of the project as stated in the approved SOW. If the application listed milestones/target dates for important activities or phases of the project, identify these dates and show actual completion dates or the percentage of completion.

We have two high-level goals for HandSight:

1. **First, to develop the basic building blocks of an extensible HandSight platform** that will support a range of ADL applications. This includes: (i) *developing computer vision and machine learning algorithms* to support basic sensing needs from a finger-mounted camera (*e.g.*, optical character recognition, surface and color classification, gesture recognition); and (ii) investigating physical design and feedback modalities (*e.g.,* augmenting one *vs.* both index fingers, using directional haptic feedback to guide the user's touch).

2. **Second, to explore and demonstrate the potential of HandSight** through three proof-of-concept applications: reading, dressing, and technology access. Our goal to demonstrate the benefits of HandSight both for blind users and for the larger VI population. The VA estimates that 157,000 US Veterans are legally blind, and more than *one million* have low vision [2]. Unobtrusively reading text, for example, holds significant promise for both populations.

In the first year of our funded work, we have focused largely on the first high-level goal—that is, developing the basic components for an extensible platform—including designing and iterating on physical form factors, developing computer vision algorithms to extract attributes of the physical world and to support on-body interaction, and experimenting with haptic feedback options to guide the user's finger/hand.

Below, we list the tasks from our *SOW* and approximate completion rates. We enumerate what was accomplished for these tasks in the next section (note: if a task is not listed below, then no work has been accomplished in that area).

- Task 1: Develop responsive haptic feedback: ~75% complete
- Task 2: Develop physical form factor: ~25% complete
- Task 3: Develop sensing algorithms and evaluate using controlled datasets: ~35% complete
- Task 4: Design, build, and evaluate a reading application: ~30% complete
- Task 6: Design, build, and evaluate technology access application: ~25% complete

What was accomplished under these goals?

For this reporting period describe: 1) major activities; 2) specific objectives; 3) significant results or key outcomes, including major findings, developments, or conclusions (both positive and negative); and/or 4) other achievements. Include a discussion of stated goals not met. Description shall include pertinent data and graphs in sufficient detail to explain any significant results achieved. A succinct description of the methodology used shall be provided. As the project progresses to completion, the emphasis in reporting in this section should shift from reporting activities to reporting accomplishments.

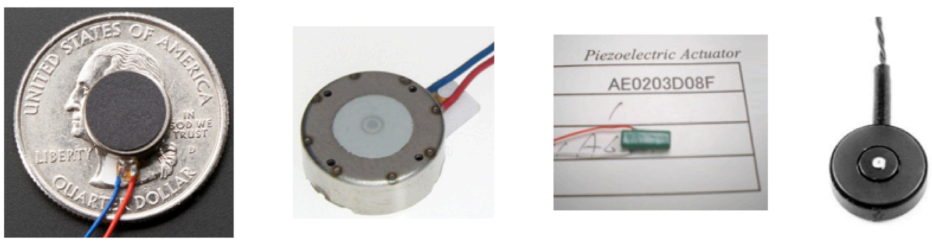
In this section, we report on our accomplishments for Tasks 1 – 4 and Task 6. While the Tasks themselves share many overlapping pursuits (*e.g.,* the physical design and hardware impacts nearly every Task), we attempt to describe the main aspects of each Task separately.

TASK 1: DEVELOP RESPONSIVE HAPTIC FEEDBACK: ~75% COMPLETE

For many ADL tasks, we need to actively guide the user's finger, hand, or even arm toward or along some object. For example, in the reading task (Task 4), the user's finger needs to be guided along lines of text in order for the finger-worn camera to scan and read words. Thus, Task 1 focuses primarily on how to use haptics (*e.g.,* vibration, pressure, etc.) to guide the user's finger and hand movement to accomplish some goal (*e.g.,* reading printed text). Our Task 1 progress can be broken into three categories of work: (i) exploring and experimenting with haptic hardware; (ii) designing, developing, and evaluating finger-mounted haptic guidance; and (iii) designing, developing, and evaluating wrist-mounted haptic guidance. While our SOW describes a controlled lab study of the most promising haptic feedback options at the Atlanta VA in months 9-11, we have not yet conducted this study. However, we meet weekly with our Atlanta VA co-PI, David Ross, have sent one graduate student to Atlanta to work with and present to David and his colleagues about our progress, and plan to run this user study by the end of 2015.

Task 1.1: Exploring and Experimenting with Haptic Hardware

We surveyed 14 commercial haptic hardware options informed by the haptics' research literature and our own online searches. We purchased and informally evaluated seven of these options including piezoelectric actuators [37], Dynalloy Flexinol actuator wire [9], standard vibrating motor discs (such as those found in cell phones) [38, 45], and the C-3 Tactor [4]. See Figure 1 for some example haptic actuators we have explored. Based on price, size, operating characteristics, and the results from informal experiments, we selected the vibrating motor discs (far left in Figure 1) for our initial haptic studies but we will continue to experiment with and explore other options. As noted in a previous report, we are having some trouble finding haptic solutions that are as small as our camera hardware, which consequently increases the size of the entire HandSight prototype.



Cheap Motor	Precision Microdrives LRA	Piezoelectric Actuator	C-3 Tactor
10mm	10mm	2x3x10mm	20mm
$2	$10	$33 + $100 driver	$340

Figure 1: Four example haptic actuators we have purchased and examined in our lab.

Task 1.2: Designing, Developing, and Evaluating Finger-Mounted Haptics

To help us study haptic options in detail, we developed an iPad-based test apparatus. Here, blind/low-vision participants can complete finger-guidance tasks—*e.g.,* trace a line, trace a shape, follow lines of text—and we can record precise finger movements (*e.g.,* finger position, velocity, acceleration and proximity to the projected shape). A thin sheet of paper covers the iPad to simulate the feeling of paper (this does not affect the capacitive finger-location sensing of the iPad). See Figure 2.

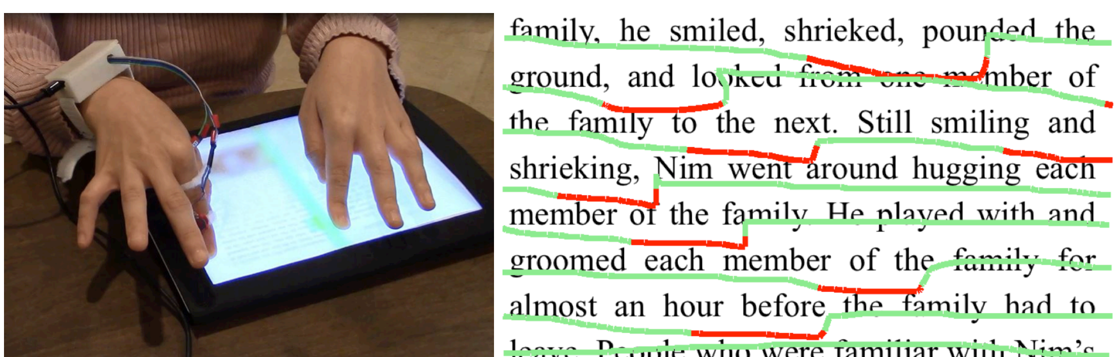


Figure 2: (left) The iPad testbed setup for our lab studies. (right) The precise finger traces collected by our custom iPad test application (green/red lines are actual finger traces from a participant in the TACCESS study; green=on line so no feedback provided and red=feedback provided).

Finger-mounted haptic prototype. Our finger-mounted haptic prototype consists of two disc vibration motors (8mm diameter, 3.4mm thick) controlled by an Arduino Pro Micro that communicates with the iPad via Bluetooth. The motors are attached to the user's right index finger with separate Velcro rings (Figure 3), one on top of the finger on the intermediate phalange and one below the finger on the proximal phalange. The lower motor indicates that the finger should move downward and the upper motor indicates the opposite. Neither motor vibrates while the user's finger is directly over the current line of text. Vibration intensities off the line range from a minimum perceptible strength to the maximum strength the motors can provide, using distance thresholds. The choice to vary the position and intensity of vibration to indicate direction and distance was also motivated by our prior work and validated in pilot sessions. We conducted three studies of this general approach published across three venues—all in the context of a finger-reader application (Task 4 in our SOW). We summarize findings below and ask that you consult the specific publications for details.

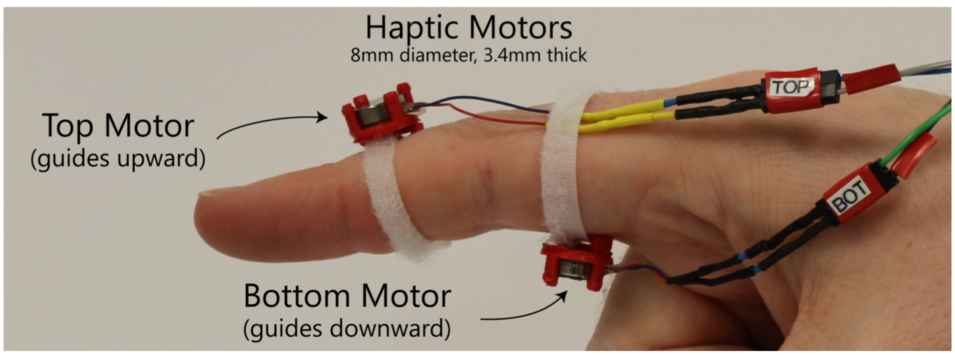


Figure 3: Close-up view of the haptic motor configuration used in our TACCESS research. They are both mounted on the finger via Velcro rings. The top motor vibrates when the user's finger moves below the line, providing upward guidance; the bottom motor vibrates when the user's finger moves above the line, providing downward guidance. The intensity of vibration depends upon the distance to the line, achieving maximum intensity at 127 pixels (~2.4 cm).

Initial study (ACVR'14 [43]**).** We ran an initial study with four blind participants comparing an initial finger-based haptic feedback prototype to pitch-controlled audio with our iPad testbed. In short, we found that three participants preferred the audio condition while one preferred combined audio+haptics. While preliminary, these findings suggest that an audio channel should be considered in addition to a haptic guidance channel for precise guidance tasks such as line-by-line reading with a finger. These results are published at ACVR'14 [43].

Follow-up studies (ASSETS'15 [7]**), in submission to TACCESS** [42]**).** In follow-up work currently in submission to ACM Transactions on Accessible Computing (TACCESS) [42], the top accessibility journal in Human-Computer Interaction, we conducted two lab studies with blind persons: (i) a comparison of audio and haptic directional finger guidance with 20 blind participants using an updated version of our iPad-based testbed and a refined version of our haptic setup, and (ii) a smaller proof-of-concept study with 4 blind participants using a preliminary wearable prototype with physical paper. The primary goal of the first study was to compare the effects of the two guidance methods in terms of line tracing accuracy, reading speed, comprehension, and subjective response. The second study explored the experience of using HandSight to read printed documents and compared it with a popular mobile application, KNFB Reader iOS.

In the first study, we found similar performance between haptic and audio directional guidance, although audio offered a slight accuracy advantage for line tracing. Subjective feedback also highlighted tradeoffs between the two types of guidance, such as the interference of audio guidance with speech output and the potential for desensitization to haptic guidance. While several participants appreciated the direct access to layout information provided by the finger-based reading approach, important concerns also arose about ease of use and the amount of concentration required to read in this way. See the paper for details.

Task 1.3: Designing, Developing, and Evaluating Wrist-Mounted Haptics
In addition to the finger-mounted haptic approach described above, we have also designed, developed, and evaluated a wrist-mounted haptic approach. As our envisionment for HandSight includes a smartwatch for processing and power, we wanted to explore how the *wristband* itself could be used to provide useful haptic feedback to the user. The wrist offers a balance between proximity, sensitivity [5], surface area, and social acceptability. The larger surface area, for example, allows for a greater number of vibration sources than the finger. Similar to the finger-mounted haptics research, we pursued a human-centered, iterative design approach starting with ideation and the informal exploration of a number of initial physical prototypes, followed by a series of iterative refinements, then more formal experiments with externally recruited participants. The physical designs are described in the Task 2 section.

We are currently exploring physical form factors, number and type of embedded wristband haptic devices, and haptic modulation approaches (*e.g.,* pulse, continuous, frequency, etc.). Thus far, we have investigated three types of tasks: (i) direction, (ii) target finding, and (iii) and route tracing. To examine these tasks experimentally, we created another testbed similar to that used in Task 1.2—this time, however, on an Android tablet rather than an iPad (Android screenshots are in Figure 4). While we have tested each of these tasks in our lab with pilot participants, we have conducted a formal experiment with only the first task (direction), which we describe below. Other tasks will be examined soon with VI users at the Atlanta VA led by co-PI David Ross.

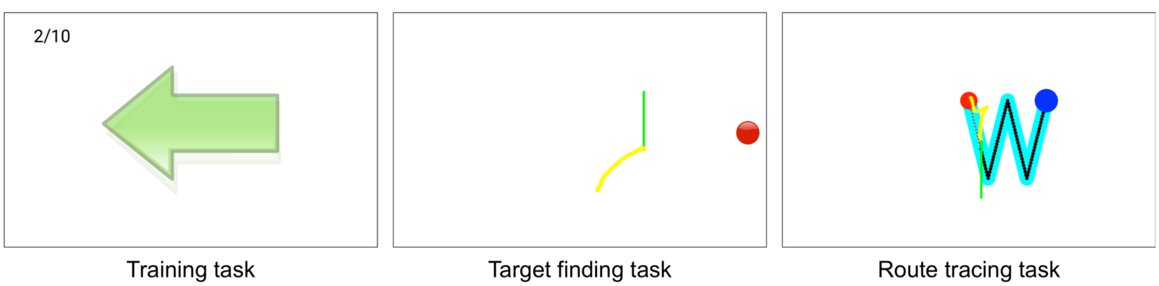


Figure 4: Two of the three experimental tasks in our Android application: the (ii) target finding task and the (iii) route tracing task. The visuals are for illustration only and would not be seen by participants. The yellow line in the target-finding and route-tracing tasks shows the finger trace so far, while the green line (up or down) indicates which motor is currently vibrating on the user's wrist.

Initial study (in submission to CHI'16). In this work, we performed a controlled lab experiment to evaluate the impact of wrist-based vibro-motor feedback on directional hand movement, comparing lower-fidelity (4-motor) and higher-fidelity (8-motor) wristbands. Twenty sighted participants completed a series of non-visual trials consisting of interpreting a haptic stimuli and executing a 2D directional movement on a touchscreen. We assessed movement error and trial speed, but also conducted a deeper analysis of the impact of specific directions on performance.

The haptic feedback worked as follows: vibration frequency was controlled by pulse-width-modulation (PWM) from the Arduino; higher voltage corresponded to higher vibration frequency. The frequency range used for the experiment was 62–156 Hz, which we determined through two mechanisms. First, to ensure that we accurately used voltage to manipulate vibration frequency, we evaluated the relationship between voltage and frequency when the motor is worn on the wrist. As shown in Figure 5d, this relationship was roughly linear above 1.2V, up to a maximum frequency of 156Hz at 3V. Second, to ensure that the full frequency range was perceptible by users, we conducted a simple perception test with 6 participants from our lab. We increased the frequency continuously from 0 Hz until the participant reported a light vibration, then decreased it from 156 Hz until no vibration was felt. To be conservative, we selected the maximum value among all reported thresholds (62 Hz) as a perceptible lower bound on our vibration range.

To indicate a target direction, one or two motors vibrated. If the direction coincided exactly with a motor's placement, that single motor vibrated at maximum frequency (156 Hz). If the direction was between two motors, those motors vibrated with linearly interpolated frequencies within the 62–156 Hz range. For example, 45° is exactly between two motors on the 4-motor wristband, so those motors vibrated at the same frequency, while for 70°, one motor vibrated at higher frequency than the other. More formally:

$$f_1 = (\theta_2 - \theta - \theta_{start})\frac{f_{max} - f_{min}}{\theta_2 - \theta_1 - \theta_{start}} + f_{min},$$

$$f_2 = (\theta - \theta_1 - \theta_{start}) * \frac{f_{max} - f_{min}}{\theta_2 - \theta_1 - \theta_{start}} + f_{min}$$

where $f_{max} = 156$, $f_{min} = 62$, θ_1 and θ_2 indicate the motor placements and θ is the target direction ($\theta_2 > \theta > \theta_1$). To use the full range of perceptible frequencies, the second motor did not begin vibrating until $\theta_{start} \geq 11.25°$ past θ_1.

The contributions of this study include: (i) empirical evidence that doubling the number of haptic motors reduces directional movement error and that movement error is greater to the upper-left than in other directions; (ii) identification of a maximum threshold of ~25° accuracy using our approach; (iii) design considerations for incorporating directional haptic guidance into a smartwatch band. A description of the hardware and physical design is provided in Task 2.1 below.

TASK 2: DEVELOP PHYSICAL FORM FACTOR: ~25% COMPLETE

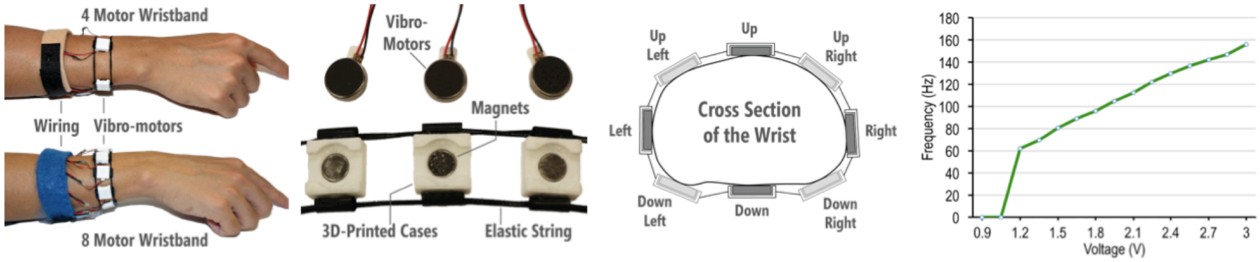
At a high-level, the physical design of HandSight can be broken down into four categories of work: (i) identifying and experimenting with camera, haptic, smartwatch, and wristband hardware, (ii) exploring where and how to mount the camera and haptics (*e.g.*, rings, glovces) and trying to understand the advantages/disadvantages of each placement on algorithm performance and user comfort, (iii) exploring more holistic aspects of the design such as wiring, power, etc., (iv) exploring the aforementioned usability aspects. The physical design and form factor of HandSight impacts everything from user comfort to the design and operation of our algorithms. For example, a finger-mounted camera on the proximal phalange will have a larger field-of-view than one mounted on the intermediate or distal phalange for up-close interactions—this would allow the camera to see more information and, perhaps, make object/text recognition easier. Similarly, in investigating camera hardware and lenses, we are interested in optimizing for size, power usage, and resolution with a large field-of-view, adaptive focus, and self-illumination. Higher resolution, self-illumination, and an adaptive focus eases many computer vision problems such as dealing with shadowing, image artifacts due to low resolution capture, etc. Thus far, our focus has been primarily on creating *functional* form factors (*i.e.,* categories (i) and (ii)) rather than attractive, robust, or aesthetic form factors. Our focus will shift to these latter attributes once we have determined a promising functional design.

Task 2.1 Finding and Experimenting with Hardware
Below, we describe the hardware related to the camera, haptics, audio, and smartwatch.

Camera hardware. HandSight's primary sensing hardware consists of one or more finger-mounted cameras. The current single-camera prototype uses a $1\times1mm^2$ *AWAIBA NanEye 2C* camera [33] that can capture 250×250 resolution images at 44 frames per second (fps). The NanEye was originally developed for minimally invasive surgical procedures such as endoscopies and laparoscopies and is thus robust, lightweight, and precise. We have also explored a NanEye camera with four LEDs coincident with the lens, which allows for increased illumination control. This is the camera used in both our ACVR'14 and TACCESS work. More recently, we have experimented with a stereo NanEye version, which is larger, but may be able to provide depth and proximity information (2×44fps, $1\times2.2mm^2$) and a faster, higher resolution NanEye camera (100fps, 640×640, $3.4\times3.4mm^2$), which again though larger, may allow us to more accurately compute optical flow during finger movement (as indicated by previous work [47]).

While the NanEye cameras have received most of our attention**,** we have also explored other options. Below, we list the full range of cameras we have investigated via informal testing in our lab along with pros/cons. The infrared (IR) cameras listed are for future work related to the on-hand localization research described in Task 3.2 (specifically, they are used for vein detection).

- **NanEyes**: http://www.cmosis.com/products/product_detail/naneye_module
  - NanEye 2C, NanEye GS, and NanEye GS Stereo
  - Extremely tiny with good image quality & focal length; high frame rate & programmable
  - Very expensive
- **Microlens**: http://www.amazon.com/gp/product/B009N8JL9Q/
  - Portable Microscope used in CVPR'16 research
  - Adjustable focal length (as close as 1cm), good image quality
  - Very large, requires manual LED and focal length adjustments
- **Endoscope/Boroscope**: http://www.amazon.com/Newest-Endoscope-Borescope-Insepction-Camera/dp/B00MNBKFHC/
  - Cheap and durable
  - Low frame rate, bad image quality, fixed focus (infinite)
- **Sony Playstation Eye**: http://www.amazon.com/Sony-PlayStation-Camera-Bulk-Packaging-Pc/dp/B0072I2240
  - Sony Playstation Eye camera with IR filter removed and visible light filter added
  - For vein detection
  - Very cheap, easily hackable
  - Small for a webcam, but too large to be wearable on the finger
- **Kinect**: http://www.xbox.com/en-US/xbox-360/accessories/kinect
  - Microsoft Kinect for Windows v1
  - Good quality IR images for vein detection (includes 850nm filter)
  - Programmable, easily switches between IR and RGB
  - Large, low resolution, and fixed focal length > 1ft
- **Raspberry PI NoIR**: https://www.raspberrypi.org/products/pi-noir-camera/
  - Raspberry Pi NoIR camera with external visible light filters
  - Good image quality, manually adjustable focal length, small, programmable



(a) (b) (c) (d)

Figure 5: **(a)** The four- and eight-motor haptic wristband prototypes. **(b)** A close-up of our haptic design; motors were placed in the 3D-printed cases using magnetic attachments, and the wristband faced downward so that the motors directly contacted the skin. **(c)** Our custom-designed wristband could accommodate wrists of various shapes and sizes. Motor placement was adjusted per participant to match this figure. **(d)** A voltage input *vs.* vibration frequency response graph as measured using a piezoelectric sensor while the motor was worn on a wrist. Results were used to verify a linear relationship between voltage input and frequency and to empirically determine minimum voltage.

Wristband Haptics (in submission to CHI'16). Our initial hardware implementation for finger-mounted haptics is described in Tasks 1.1 and 1.2 above. Here, we describe the four-vibromotor and eight-vibromotor wristbands used in our first wrist-based haptics study (in submission to CHI'16). The wristbands, shown in Figure 5a, were identical except for the number of motors (four or eight). We used circular disc vibro-motors 10 mm in diameter, with maximum voltage of 5V and maximum frequency of 183Hz.[1] These motors are inexpensive and ubiquitous, and the flat design means they can be easily integrated into a future envisioned smartwatch wristband. Our custom design addresses three issues: vibration transfer along the band, variation in wrist size, and the non-uniform shape of a wrist. To effectively isolate the motors and limit vibration transfer—an issue in our early designs—we mounted the motors on a band separate from the wiring and housed them magnetically in 3D-printed cases connected only by thin elastic thread (Figure 5b). The band with the wiring in turn connected to the Arduino for communication and power.

Because the wrist is not a uniform oval (Figure 5c), placing the motors equidistantly around the band (as in [41, 46]) means that the motors are not necessarily at the position the user expects—for example, the right-most location on the wrist may not be midway between the up and down positions. To address variation in wrist sizes and shapes, our prototype is adjustable. The band with the motors is threaded through the motor cases rather than affixed, which allows the cases to slide (with effort) along the band, and allows the band to be tightened or loosened (based on [17]). Thus, the wristband could be easily reconfigured to support a wide range of wrist sizes.

Audio. We have used audio to both complement the haptic channel (*e.g.,* notifications) as well as to serve as a baseline condition for some experiments. Currently audio signals are conveyed via a tablet or laptop but will be incorporated directly into future smartwatch designs.

Smartwatch. For the smartwatch, we have largely relied on our own prototype substitute—a small Arduino board with custom 3D printed case and wristband. We expect to replace this with an Android-based smartwatch in the future.

TASK 3: DEVELOPING & EVALUATING SENSING ALGORITHMS: ~35% COMPLETE
As previously noted, we have two main interrelated objectives for HandSight: first, to develop the basic building blocks of an extensible platform and second, to explore and demonstrate the potential of HandSight through three proof-of-concept applications in reading, dressing, and

technology access. Below, we describe our progress thus far in developing and evaluating our camera-based sensing and inference algorithms for the latter two of these application areas: reading and technology access.

Task 3.1 Developing Real-time OCR with Finger-Mounted Camera

While our long-term plan is to integrate real-time OCR processing into a smartwatch, the algorithm presented below was run on a laptop connected directly to the finger-mounted camera. Our current HandSight implementation involves a series of frame-level processing stages followed by multi-frame merging once the complete word has been observed. Below, we summarize our five-stage OCR process and some preliminary experiments evaluating performance. For more detail, see our ACVR'14 paper.

Stage 1: Preprocessing. We acquire grayscale video frames at ~40fps and 250x250px resolution from the NanEye camera (Figure 6). With each video frame, we apply four preprocessing algorithms to correct radial and (slight) tangential distortion, to control lighting for the next frame, to reduce noise, and to reduce false positives.

Stage 2: Perspective and Rotation Correction. To correct perspective and rotation effects, we apply an efficient approach that relies on the parallel line structure of text for rectification.

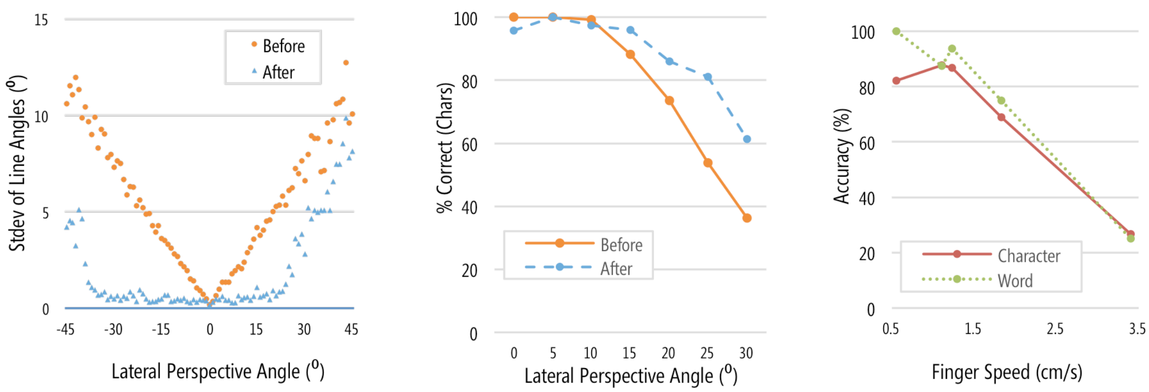
Figure 6: A demonstration of our perspective and rotation correction algorithm.

Stage 3: Text Detection. The goal of the text detection stage is to build up a hierarchy of text lines, words, and characters. We split the image into lines of text by counting the number of text pixels in each row and searching for large gaps, then segment lines into words using a similar process, and finally segment each word into individual characters by searching for local minima in the number of text pixels within each column.

Stage 4: Character Classification. Real-time performance is important for responsive feedback, which prevents us from using established OCR engines such as Tesseract. Thus, we compute efficient character features and perform classification using a support vector machine (SVM).

Stage 5: Tracking and final OCR result output. The camera's limited field of view means that a complete word is seldom fully within a given frame. We must track the characters between frames and wait for the end of the word to become visible before we can confidently identify it. Character tracking uses sparse low-level features for efficiency. First, we extract FAST corners [40], and apply a KLT tracker [44] at their locations. We estimate the homography relating the matched corners using the random sample consensus [8]. After determining the motion between frames, we relate the lines, words, and individual characters by projecting their locations in the previous frame to the current frame using the computed homographies. The bounding boxes with the greatest amount of overlap after projection determine the matches. When the end of a word is visible, we sort the aggregated character classifications and accept the most frequent classification. This process can be improved by incorporating a language dictionary model, albeit at the expense of efficiency. A text-to-speech engine reads back the identified word.

Algorithm Evaluation. We investigated the effect of camera perspective and rotation on OCR accuracy as well as the effect of finger movement speed on OCR accuracy. For the former, we created an artificially rotated and distorted our images and tested the resulting performance of our algorithms (Figure 7a and b). For the latter, we recorded five different speeds using a single line of text. The results are presented in Figure 7c. With greater speed, motion blur is introduced, and feature tracking becomes less accurate. In our experience, a "natural" finger speed movement for sighted readers is roughly 2-3cm/s. So, with the current prototype, one must move slower than natural for good performance. We plan on compensating for this effect in the future using image stabilization and motion blur removal, as well as incorporating a higher frame rate camera (100fps). Other future work is described later in the 'plans for next reporting period' section.



(a) Performance of lateral perspective and rotation rectification algorithm. **(b)** Effect of lateral perspective angle on accuracy (before and after correction). **(c)** Effect of finger speed on character- and word-level accuracy.

Figure 7: Results from preliminary evaluations of our (a-b) Stage 2 algorithms and (c) the effect of finger speed on overall character- and word-level accuracy.

Task 3.1 Developing On-Hand Localization Algorithms

While we primarily envision HandSight as enabling access to the physical world, we are also exploring another use case: increasing mobile technology access through on-body interaction. Mobile devices have become critical to everyday tasks from communication to navigation, yet persistent accessibility challenges remain [48]. As an alternative to the touchscreen, HandSight will allow users to control the screenreader software on their mobile device by making taps or swipes on their *own hands*. Users who do not need a visual display will thus not need to pull the device out of their pocket or bag. On-hand gestures should also offer increased tactile and proprioceptive feedback compared to the smooth surface of the touchscreen. While arbitrary surface input has been previously proposed [3, 13–15, 29, 32, 47], its potential to improve technology access has been overwhelmingly ignored (with one small exception [14]).

We aim to investigate two specific on-hand interactions to increase mobile accessibility: (i) detecting and localizing on-hand taps (*e.g.,* a blind user tapping on a specific finger tip to invoke an action on their mobile device) and (i) detecting gestures (*e.g.,* a blind user swiping across a specific location on their palm to silence an alarm). To our knowledge, such localization has never been done with finger-mounted cameras. We describe work below that will be submitted to CVPR'16 in early November (CVPR is one of the premiere publication venues in computer vision).

Initial On-Hand Interaction Algorithm Work (to be submitted to CVPR'16 in November). Since the palm and fingers offer a high density of discriminable features that are well studied in the context of biometrics [22, 25, 49], they are a promising surface for image-based localization. Proprioceptive sensitivity has also been shown to be greatest on the tips of the fingers and the palm of the hand [11], making them an appealing choice for a touch surface. However, other locations may also work well; in this work we explore several different regions, including the fingers and palm as well as fingernails, knuckles, wrist, and back of the hand.

Our approach extends [47] for on-body input, using a hierarchical texture classifier to estimate the approximate touch region on the body (see Table 2), given a close-up images of the surface. We then refine the location estimate using keypoint matching and geometric verification. Although we focus primarily on the hand as an input surface due to its size, sensitivity, and visually discriminable features, our approach is flexible enough to adapt to other body locations or general surfaces as well. We evaluate our classification algorithms on a dataset consisting of 30 individuals and 17 different close-up regions on the hand (Figure 8; 10,198 micro-lens images in all), achieving a preliminary average classification accuracy of 96.4% using n-fold cross validation. More detailed results are shown in Tables 1-3.

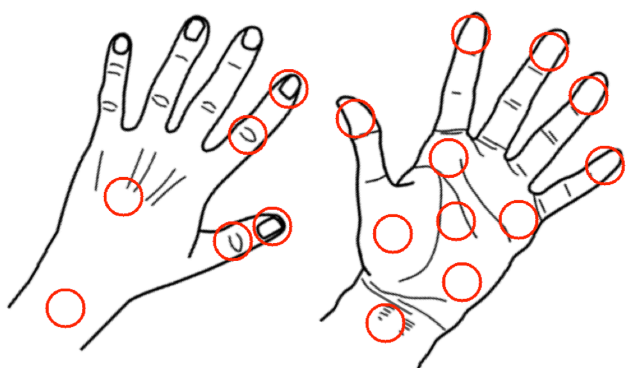


Figure 8: Seventeen locations of images being collected and classified for the on-hand localization algorithmic work.

Algorithmic Robustness

Variable	Conditions	Average Accuracy Across 17 Locations
Rotation	*15° increments*	99.7% (*SD*=0.4%)
Translation	*25%-100% overlap*	98.2% (*SD*=2.3%)
Scale	*0.5x–2x*	78.9% (*SD*=27.5%)
Lighting	*Overhead/Left/Right*	52.5% (*SD* N/A)
Pose	*Extended/Relaxed*	58.0% (*SD* N/A)

Table 1: Results of a series of algorithmic robustness experiments using a synthetic database of 99000 images with known parameters.

Group-Level Confusion Matrix

	Palm	*Finger*	*Nail*	*Knuckle*	*Other*
Palm	**99.0%**	0.5%			0.5%
Finger	0.6%	**99.3%**	0.1%		
Nail	0.2%	0.1%	**99.7%**	0.1%	
Knuckle			0.2%	**99.1%**	0.7%
Other	0.6%		0.1%	0.5%	**98.8%**

Table 2: Classification accuracy for classes at the group level. Each cell indicates the percentage of images assigned to a predicted class (column) for each actual class (row).

	Palm					Fingers					Nails		Knuckles		Other		
	C	*U*	*D*	*L*	*R*	*1st*	*2nd*	*3rd*	*4th*	*5th*	*1st*	*2nd*	*1st*	*2nd*	*BH*	*OW*	*IW*
Palm Center	**98.3%**					0.2%		0.2%		0.2%					0.2%	0.5%	0.5%
Palm Up	0.2%	**98.5%**		0.2%	0.2%		0.2%			0.3%						0.2%	0.3%
Palm Down	0.3%	1.2%	**95.7%**	0.2%	1.7%	0.3%	0.2%						0.2%			0.2%	0.2%
Palm Left	0.3%	0.3%	0.2%	**98.7%**	0.3%	0.3%											0.7%
Palm Right	0.7%	0.5%	0.3%	0.5%	**97.5%**	0.2%	0.2%			0.2%							
1st Finger		0.5%	0.2%	0.2%	0.7%	**96.3%**	0.3%	0.5%	0.5%	0.7%					0.2%		
2nd Finger		0.3%			0.2%	0.3%	**95.8%**	1.7%	0.5%	1.2%							
3rd Finger			0.3%			0.2%	1.3%	**95.4%**	2.2%	0.7%							
4th Finger			0.2%				0.3%	1.8%	**95.3%**	2.3%							
5th Finger		0.2%		0.2%			0.3%	0.5%	1.5%	**97.0%**	0.3%						
1st Nail				0.2%							**98.2%**	1.7%					
2nd Nail			02%						0.2%		0.5%	**99.0%**		0.2%			
1st Knuckle											0.2%		**97.3%**	1.2%	0.2%	0.2%	1.0%
2nd Knuckle												0.2%	0.8%	**98.8%**		0.2%	
Back of Hand				0.2%									0.5%	0.2%	**92.2%**	4.7%	2.3%
Outer Wrist	0.2%												0.2%		6.0%	**90.2%**	3.5%
Inner Wrist	0.7%	0.7%	0.2%	0.2%	0.3%						0.2%		0.7%	0.2%	0.8%	0.5%	**96.2%**

Table 3: Classification accuracy for classes at the region level, averaged across 20 trials and 30 participants. Each cell indicates the percentage of images assigned to a predicted class (column) for each actual class (row).

The contributions of this work include: (i) robust algorithms for recognizing several different regions of the hand, which will enable on-body interactions using a wearable finger-mounted camera; (ii) classification results for a preliminary dataset consisting of 30 individuals, achieving 96.4% average accuracy; (iii) analysis of palm distinctiveness and similarities between users, which may impact accuracy and scalability. See paper for details.

TASK 4: DESIGN, BUILD, & EVALUATE READING APP: ~30% COMPLETE

The progress on Task 4 has largely been covered by the above sections. In summary, while we have built an initial real-time finger-reading hardware prototype, most of work has focused on guiding the user's finger/hand along a page of text (to appropriately scan the words). In our ACVR'14 paper [43], we present an initial HandSight hardware prototype with a single finger-mounted camera and two haptic rings that provide continuous line-by-line guidance. The finger camera-based OCR algorithms were evaluated experimentally with synthetically derived data while the system itself was evaluated in an initial user study with four VI users. We conducted a follow-up study (in submission to TACCESS [42]) with 19 blind participants, comparing audio and haptic directional finger guidance within an iPad-based testbed. We later asked four of those participants to return and provide feedback on a slightly updated wearable prototype from the ACVR work. Findings from the controlled experiment show similar performance between haptic and audio directional guidance, although audio may offer an accuracy advantage for tracing lines of text. While several participants appreciated the direct access to layout information provided by finger-based exploration of text, important concerns also arose about ease of use and the amount of concentration required to read in this way.

TASK 6: DESIGN, BUILD, & EVALUATE ON-HAND ACCESS APP: ~25% COMPLETE

Similar to Task 4, the progress for this task has already been described in a related section (Task 3.1) above. To summarize: though pervasive, touchscreen input may be inaccessible for users with visual impairments, or in certain contexts when users cannot afford visual attention (*e.g.*, driving), as it heavily on visual feedback. On-body input, which is performed on the user's own body, could be a potential solution since tactile feedback from the skin enables users to acquire desired target more precisely without visual feedback [14]. For example, users could use the palm of their hand as a substitute for a mobile phone's touchscreen, performing tap and swipe gestures to control the phone. Alternatively, particular locations could be tied to intuitive commands, such as tapping on the wrist to check the time or on the ear to answer a phone call. This input mechanism may be especially beneficial for people with visual impairments [26, 35]. In our current work (which, as previously noted, will be submitted to CVPR'16 in early November), we explore computer vision approaches to automatically recognizing regions on the finger, palm, as well as fingernails, knuckles, wrist, and the back-of-the-hand. Using a dataset consisting of 30 individuals and 17 different close-up regions on the hand, our algorithms achieve an average classification accuracy of 96.4%. However, this system is not yet wearable and our algorithms do not run in real-time (this remains future work).

What opportunities for training and professional development has the project provided?
If the project was not intended to provide training and professional development opportunities or there is nothing significant to report during this reporting period, state "Nothing to Report."

Describe opportunities for training and professional development provided to anyone who worked on the project or anyone who was involved in the activities supported by the project. "Training" activities are those in which individuals with advanced professional skills and experience assist others in attaining greater proficiency. Training activities may include, for example, courses or one-on-one work with a mentor. "Professional development" activities result in increased knowledge or skill in one's area of expertise and may include workshops, conferences, seminars, study groups, and individual study. Include participation in conferences, workshops, and seminars not listed under major activities.

As university professors, we work closely with undergraduate and graduate students on our research projects. HandSight is no different. Thus far, the HandSight project has involved the following students (see also Section 7, which provides a more detailed list of personnel and roles; asterisks indicates funded on grant):

PhD Students: Uran Oh*, Lee Stearns*, Jonggi Hong*, Ruofei Du
Masters Students: Anis Abboud*
Undergraduate Students: Eric Lancaster, Bridget Cheng, Tony Cheng, Catherine Jou, Weishen 'Victor' Chen, Andrew Matuza, Yumeng 'Mandy' Wang

Our PhD students lead different parts of the project and gain expertise in those areas: for example, Lee Stearns is leading the computer vision component of the work, Jonggi Hong the haptics portion, and Uran Oh, the general user experience. Our PhD students also help supervise undergraduate students in those areas. All students gain both technical skills in their areas (*e.g.,* computer vision, haptics), skills related to designing and running studies (*e.g.,* experimental design, analysis, running study sessions themselves), and general research skills (*e.g.,* analyzing data, writing papers). Our team meets once a week with all students and PIs/co-PIs. David Ross joins us remotely via a video chat interface. PIs Froehlich and Findlater also conduct weekly 1:1 meetings with the graduate students.

How were the results disseminated to communities of interest?
If there is nothing significant to report during this reporting period, state "Nothing to Report."

Describe how the results were disseminated to communities of interest. Include any outreach activities that were undertaken to reach members of communities who are not usually aware of these project activities, for the purpose of enhancing public understanding and increasing interest in learning and careers in science, technology, and the humanities.

Our team attempts to disseminate the results of our work broadly via scientific publications, research talks and posters, and online videos. Thus far, we have presented two peer-reviewed publications at ACVR'14 [43] and ASSETS'15 [7]. We also have three papers either in submission or nearing submission: TACCESS, CHI'16, and CVPR'16 (see above for details).

PIs Froehlich and Findlater often include HandSight in their invited talks. For example, PI Findlater was recently invited to give a talk at the University of Illinois, Urbana-Champaign where she included content on HandSight.

We also disseminate our work beyond the academic community via YouTube videos, webpages, and tutorials. For example, an initial HandSight video is available on YouTube here: https://youtu.be/AWCEDYdwBAc. Moreover, you can read about an early (pre-funded) HandSight prototype on Instructables: http://www.instructables.com/id/HandSight-A-Glove-for-the-Blind-to-Feel-Shapes-an/ where it has been viewed over 21,000 times and favorited 107 times.

Describe briefly what you plan to do during the next reporting period to accomplish the goals and objectives.

TASK 1: DEVELOP RESPONSIVE HAPTIC FEEDBACK
Our haptic feedback work has been driven by application needs and we expect this to continue. We have pursued two simultaneous haptic feedback options: finger mounted and wrist mounted. Our current and immediate focus is on the wristband haptics. Our CHI'16 work (in submission) focuses purely on directional guidance. In the next three months, we plan to run studies of target-finding and route-tracing tasks along with co-PI David ross at the Atlanta VA. Our Android testbed is fully complete, we have just been finalizing haptic feedback approaches via pilot studies before running a more formal study at the Atlanta VA.

TASK 2: DEVELOP PHYSICAL FORM FACTOR:
As we are still heavily experimenting with hardware, there are no immediate plans to further develop our physical form factor. Instead, our focus will be in building prototype enclosures and wearable straps/harnesses for our experimental hardware. This will indirectly help us improve the functional aspects of future form factors

TASK 3. DEVELOP AND EVALUATE SENSING ALGORITHMS
Real-Time OCR Algorithms. Our preliminary algorithms are efficient and reasonably accurate, but there is much room for improvement. By incorporating constraints on lower-level text features we may be able to rectify vertical perspective effects and affine skew. We can also apply deblurring and image

stabilization algorithms to improve the maximum reading speed the system is able to support. Robust and efficient document mosaicking and incorporation of prior knowledge will likely be a key component for supporting a wider range of reading tasks. Currently, our prototype relies on only local information gleaned from the on-finger camera. However, in the future, we would like to combine camera streams from both a body-mounted camera (*e.g.,* Orcam [36]) and a finger-mounted camera. We expect the former could provide more global, holistic information about a scene or text which could be used to guide the finger towards a target of interest or to explore the physical document's layout.

On-Hand Localization Algorithms. We have three key areas of future work here: increasing robustness, implementing a real-time system, and reducing training requirements. Towards robustness, while our experiments demonstrated that our algorithms are largely invariant to changes in rotation and translation, they are not yet invariant to scale, lighting, and pose (*e.g.,* stretched out hand vs. folded hand). A self-illuminated camera that is fixed in place on the user's finger will reduce variations in scale and lighting, and users could be instructed to hold their hand in a fixed pose while using the system. However, we plan to also investigate ways to improve our algorithm's robustness in the future, possibly by using a deformable three-dimensional model of the hand (*e.g.*, [27, 28]). Towards a real-time system, ultimately we want to optimize our algorithms such that they can operate on a modern smartwatch (e.g., Gear S2). Our system currently operates offline on an Intel i7 Desktop system. In the next year, we plan to optimize and adapt our algorithms to work real-time on an embedded computer. Finally, towards reducing training requirements, our current system requires between 5-10 training samples per hand region. This could be perceived as overly burdensome by some users. As a comparison, the Apple Fingerprint Recognition system requires 7-10 samples per finger; however, users are likely to only train 1 or 2 fingers. In our case, its likely that a user will want to train 5-15 separate regions on their hands (if not more). One way to lower training requirements is to find useful cross-user patterns that exist across all hands/fingers that can be used to bootstrap the system. We are currently exploring this avenue.

Color and Texture Recognition. While we had one undergraduate student (Gideon Popkin) implement some preliminary color recognition algorithms, much more work is needed here. We expect color and texture recognition will be a key part of *Task 5: Design, Build, and Evaluate a Dressing Application*, which our SOW outlines for Year 2.

TASK 4: DESIGN, BUILD, AND EVALUATE A READING APPLICATION

Most of this work will be algorithmic in the next 3-6 months as described above. We plan to experiment with a multi-camera approach (*e.g.,* two instrumented fingers or on-body + finger-mounted), which should hopefully improve recognition rates and solve problems due to limited field-of-view, blur, etc.

TASK 6: DESIGN, BUILD, AND EVALUATE TECHNOLOGY ACCESS APPLICATION

Once we have created a real-time on-hand interaction system, we plan to run user studies with VI and control participants to study how on-hand interaction compares to traditional interactions with mobile devices.

4. **IMPACT:** Describe distinctive contributions, major accomplishments, innovations, successes, or any change in practice or behavior that has come about as a result of the project relative to:

What was the impact on the development of the principal discipline(s) of the project?
If there is nothing significant to report during this reporting period, state "Nothing to Report."

Describe how findings, results, techniques that were developed or extended, or other products from the project made an impact or are likely to make an impact on the base of knowledge, theory, and research in the principal disciplinary field(s) of the project. Summarize using language that an intelligent lay audience can understand (Scientific American style).

Nothing to Report. (See also *Section 3 Accomplishments* above)

What was the impact on other disciplines?
If there is nothing significant to report during this reporting period, state "Nothing to Report."

Describe how the findings, results, or techniques that were developed or improved, or other products from the project made an impact or are likely to make an impact on other disciplines.

Nothing to Report

What was the impact on technology transfer?
If there is nothing significant to report during this reporting period, state "Nothing to Report."

Describe ways in which the project made an impact, or is likely to make an impact, on commercial technology or public use, including:
- *transfer of results to entities in government or industry;*
- *instances where the research has led to the initiation of a start-up company; or*
- *adoption of new practices.*

Nothing to Report

What was the impact on society beyond science and technology?
If there is nothing significant to report during this reporting period, state "Nothing to Report."

Describe how results from the project made an impact, or are likely to make an impact, beyond the bounds of science, engineering, and the academic world on areas such as:

- *improving public knowledge, attitudes, skills, and abilities;*
- *changing behavior, practices, decision making, policies (including regulatory policies), or social actions; or*
- *improving social, economic, civic, or environmental conditions.*

Nothing to Report

5. CHANGES/PROBLEMS: The Project Director/Principal Investigator (PD/PI) is reminded that the recipient organization is required to obtain prior written approval from the awarding agency Grants Officer whenever there are significant changes in the project or its direction. If not previously reported in writing, provide the following additional information or state, "Nothing to Report," if applicable:

Changes in approach and reasons for change
Describe any changes in approach during the reporting period and reasons for these changes. Remember that significant changes in objectives and scope require prior approval of the agency.

Nothing to Report.

Actual or anticipated problems or delays and actions or plans to resolve them
Describe problems or delays encountered during the reporting period and actions or plans to resolve them.

No major problems.

Changes that had a significant impact on expenditures
Describe changes during the reporting period that may have had a significant impact on expenditures, for example, delays in hiring staff or favorable developments that enable meeting objectives at less cost than anticipated.

No major changes.

Significant changes in use or care of human subjects, vertebrate animals, biohazards, and/or select agents
Describe significant deviations, unexpected outcomes, or changes in approved protocols for the use or care of human subjects, vertebrate animals, biohazards, and/or select agents during the reporting period. If required, were these changes approved by the applicable institution committee (or equivalent) and reported to the agency? Also specify the applicable Institutional Review Board/Institutional Animal Care and Use Committee approval dates.

Significant changes in use or care of human subjects

Nothing to Report

Significant changes in use or care of vertebrate animals.

Nothing to Report

Significant changes in use of biohazards and/or select agents

Nothing to Report

6. **PRODUCTS:** List any products resulting from the project during the reporting period. If there is nothing to report under a particular item, state "Nothing to Report."

- **Publications, conference papers, and presentations**
  Report only the major publication(s) resulting from the work under this award.

  Journal publications. *List peer-reviewed articles or papers appearing in scientific, technical, or professional journals. Identify for each publication: Author(s); title; journal; volume: year; page numbers; status of publication (published; accepted, awaiting publication; submitted, under review; other); acknowledgement of federal support (yes/no).*

  In Submission:
  1. Stearns, L., Du, R., Oh, U., Jou, C., Findlater, L., Ross, D., & Froehlich, J. Evaluating Haptic and Auditory Directional Guidance to Assist Blind Persons in Reading Printed Text Using Finger-Mounted Cameras. *In submission to ACM Transactions on Accessible Computing*.

Books or other non-periodical, one-time publications. *Report any book, monograph, dissertation, abstract, or the like published as or in a separate publication, rather than a periodical or series. Include any significant publication in the proceedings of a one-time conference or in the report of a one-time study, commission, or the like. Identify for each one-time publication: Author(s); title; editor; title of collection, if applicable; bibliographic information; year; type of publication (e.g., book, thesis or dissertation); status of publication (published; accepted, awaiting publication; submitted, under review; other); acknowledgement of federal support (yes/no).*

None

Other publications, conference papers, and presentations. *Identify any other publications, conference papers and/or presentations not reported above. Specify the status of the publication as noted above. List presentations made during the last year (international, national, local societies, military meetings, etc.). Use an asterisk (*) if presentation produced a manuscript.*

Published:

1. Stearns, L., Du, R., Oh, U., Wang, Y., Chellappa, R., Findlater, L., & Froehlich, J. E. (2014). The Design and Preliminary Evaluation of a Finger-Mounted Camera and Feedback System to Enable Reading of Printed Text for the Blind. *Workshop on Assistive Computer Vision and Robotics (ACVR'14) in Conjunction with the European Conference on Computer Vision (ECCV'14)*. doi:10.1007/978-3-319-16199-0_43
2. Findlater, L., Stearns, L., Du, R., Oh, U., Ross, D., Chellappa, R., & Froehlich, J. (2015). Supporting Everyday Activities for Persons with Visual Impairments Through Computer Vision-Augmented Touch. In *Proceedings of the 17th International ACM SIGACCESS Conference on Computers & Accessibility* (pp. 383–384). New York, NY, USA: ACM. doi:10.1145/2700648.2811381

In Submission:

1. Stearns, L., Oh, U., Cheng, B., Chellappa, R., Findlater, L., & Froehlich, J. E. (2016). Contactless Partial Palmprint Recognition: Toward a Wearable Finger-Camera System using the Hand as an Input Surface. *Will be submitted to CVPR'16 in early November, 2015*.

- **Website(s) or other Internet site(s)**
  List the URL for any Internet site(s) that disseminates the results of the research activities. A short description of each site should be provided. It is not necessary to include the publications already specified above in this section.

  - http://www.leestearns.com/projects.html (student run project website)
  - http://www.cs.umd.edu/~jonf/publications.html (PI website)
  - https://youtu.be/AWCEDYdwBAc (ACVR'14 HandSight video)
  - http://www.instructables.com/id/HandSight-A-Glove-for-the-Blind-to-Feel-Shapes-an/ (Instructable)

- **Technologies or techniques**
  Identify technologies or techniques that resulted from the research activities. In addition to a description of the technologies or techniques, describe how they will be shared.

  None.

- **Inventions, patent applications, and/or licenses**
  Identify inventions, patent applications with date, and/or licenses that have resulted from the research. State whether an application is provisional or non-provisional and indicate the application number. Submission of this information as part of an interim research performance progress report is not a substitute for any other invention reporting required under the terms and conditions of an award.

  None

- **Other Products**
  Identify any other reportable outcomes that were developed under this project. Reportable outcomes are defined as a research result that is or relates to a product, scientific advance, or research tool that makes a meaningful contribution toward the understanding, prevention, diagnosis, prognosis, treatment, and/or rehabilitation of a disease, injury or condition, or to improve the quality of life. Examples include:
  - *data or databases;*
  - *biospecimen collections;*
  - *audio or video products;*
  - *software;*

- *models;*
- *educational aids or curricula;*
- *instruments or equipment;*
- *research material (e.g., Germplasm; cell lines, DNA probes, animal models);*
- *clinical interventions;*
- *new business creation; and*
- *other.*

None

7. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

What individuals have worked on the project?
Provide the following information for: (1) PDs/PIs; and (2) each person who has worked at least one person month per year on the project during the reporting period, regardless of the source of compensation (a person month equals approximately 160 hours of effort). If information is unchanged from a previous submission, provide the name only and indicate "no change."

<u>Example:</u>

Name: *Mary Smith*
Project Role: *Graduate Student*
Researcher Identifier (e.g. ORCID ID): *1234567*
Nearest person month worked: *5*

Contribution to Project: *Ms. Smith has performed work in the area of combined error-control and constrained coding.*
Funding Support: *The Ford Foundation (Complete only if the funding support is provided from other than this award).*

Name: *Jon Froehlich*
Project Role: *PI/Professor*
Researcher Identifier (e.g. ORCID ID): *N/A*
Nearest person month worked: *3*
Contribution to Project: *No change*

Name: *Leah Findlater*
Project Role: *PI/Professor*
Researcher Identifier (e.g. ORCID ID): *N/A*
Nearest person month worked: *3*
Contribution to Project: *No change*

Name: *David Ross*
Project Role: *Co-PI/Professor*
Researcher Identifier (e.g. ORCID ID): *N/A*
Nearest person month worked: *1*
Contribution to Project: *Meets ~weekly with team via video hangout. Provides feedback on project and on drafts of papers.*

Name: *Rama Chellappa*
Project Role: *Co-PI/Professor*
Researcher Identifier (e.g. ORCID ID): *N/A*
Nearest person month worked: *1*
Contribution to Project: *Provides feedback on CV related topics on project*

Name: *Lee Stearns*
Project Role: *Graduate Student*
Researcher Identifier (e.g. ORCID ID): *N/A*
Nearest person month worked: *12*
Contribution to Project: *No change*

Name: *Uran Oh*
Project Role: *Graduate Student*
Researcher Identifier (e.g. ORCID ID): *N/A*
Nearest person month worked: *9*
Contribution to Project: *No change*

Name: *Anis Abboud*
Project Role: *Graduate Student*
Researcher Identifier (e.g. ORCID ID): *N/A*
Nearest person month worked: *1*
Contribution to Project: *No Change. Graduated in May 2015.*

Name: *Jonggi Hong*
Project Role: *Graduate Student*
Researcher Identifier (e.g. ORCID ID): *N/A*
Nearest person month worked: *6*
Contribution to Project: *No change*

Name: *Catherine Jou*
Project Role: *Undergraduate Student*
Researcher Identifier (e.g. ORCID ID): *N/A*
Nearest person month worked: *1*
Contribution to Project: *No change. Graduated in May 2015.*

Name: *Tony Cheng*
Project Role: *Undergraduate Student*
Researcher Identifier (e.g. ORCID ID): *N/A*
Nearest person month worked: *3*
Contribution to Project: *No change.*

Name: *Weishen 'Victor' Chen*
Project Role: *Undergraduate Student*
Researcher Identifier (e.g. ORCID ID): *N/A*
Nearest person month worked: *1*
Contribution to Project: *No change. Graduated in May 2015.*

Name: *Andrew Matuza*
Project Role: *Undergraduate Student*
Researcher Identifier (e.g. ORCID ID): *N/A*
Nearest person month worked: *1*
Contribution to Project: *No change. Graduated in May 2015.*

Name: *Ruofei Du*
Project Role: *Graduate Student*
Researcher Identifier (e.g. ORCID ID): *N/A*
Nearest person month worked: *2*
Contribution to Project: *No change. Stopped working on project after Q2.*

Name: *Yumeng "Mandy" Wang*
Project Role: *Undergraduate Student*
Researcher Identifier (e.g. ORCID ID): *N/A*
Nearest person month worked: *2*
Contribution to Project: *No change. Stopped working on project after Q1.*

Name: *Bridget Cheng*
Project Role: *Undergraduate Student*
Researcher Identifier (e.g. ORCID ID): *N/A*
Nearest person month worked: *3*
Contribution to Project: *Visiting undergraduate student from Cornell. Worked with Lee Stearns on CVPR data collection*

Name: *Eric Lancaster*
Project Role: *Undergraduate Student*
Researcher Identifier (e.g. ORCID ID): *N/A*
Nearest person month worked: *1*
Contribution to Project: *Working with Lee Stearns on follow-up work to CVPR paper using IR to gather sub-skin data (e.g., veins) to improve on-hand localization*

Has there been a change in the active other support of the PD/PI(s) or senior/key personnel since the last reporting period?
If there is nothing significant to report during this reporting period, state "Nothing to Report."

If the active support has changed for the PD/PI(s) or senior/key personnel, then describe what the change has been. Changes may occur, for example, if a previously active grant has closed and/or if a previously pending grant is now active. Annotate this information so it is clear what has changed from the previous submission. Submission of other support information is not necessary for pending changes or for changes in the level of effort for active support reported previously. The awarding agency may require prior written approval if a change in active other support significantly impacts the effort on the project that is the subject of the project report.

Nothing to Report.

What other organizations were involved as partners?
If there is nothing significant to report during this reporting period, state "Nothing to Report."

Describe partner organizations – academic institutions, other nonprofits, industrial or commercial firms, state or local governments, schools or school systems, or other organizations (foreign or domestic) – that were involved with the project. Partner organizations may have provided financial or in-kind support, supplied facilities or equipment, collaborated in the research, exchanged personnel, or otherwise contributed.
Provide the following information for each partnership:
<u>Organization Name:</u>
<u>Location of Organization: (if foreign location list country)</u>
<u>Partner's contribution to the project</u> (identify one or more)

- *Financial support;*
- *In-kind support (e.g., partner makes software, computers, equipment, etc., available to project staff);*
- *Facilities (e.g., project staff use the partner's facilities for project activities);*
- *Collaboration (e.g., partner's staff work with project staff on the project);*
- *Personnel exchanges (e.g., project staff and/or partner's staff use each other's facilities, work at each other's site); and*
- *Other.*

Nothing to Report.

8. SPECIAL REPORTING REQUIREMENTS

None to report

9. APPENDICES:

Appendix A: References

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