Optical Detection of Finger Pressure through Utilization of Nailbed Color Changes

by

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ABSTRACT

This thesis presents the theory and design of a sensor that detects a when a finger is pressed by visually examining a user's fingernail coloration. Unlike other finger-based controllers that primarily depend on covering the finger pad, this method of sensing allows for accurate measurements without impairing a user's tactile sense. First the color change of a fingernail is examined based on the underlying biological mechanisms of the finger. Then the hue, saturation, and value (HSV) coordinates of videos of the fingernails are analyzed in three different locations; the entire image, a segment of the rear of the fingernail, and a segment of the tip of the fingernail. The front of the fingernail, where a white band develops when pressure is applied to the finger, proved to have statistically significant increases in saturation and value for all test subjects. With these results a simple sensor was designed and tested that accurately sensed finger presses, however with a significant time lag. Finally, the mechanical design of such a sensor was proposed, leaving room for further study and development.

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1. Introduction

As robotic innovation advances there is a growing need for development in human-robot control methods. One popular and promising avenue of study involves control determined by the measurement and analysis of finger pressure by humans. The dexterity of human fingers provides many options for control schema and, given the natural ability of humans in controlling and manipulating objects with their fingers, finger-based controllers are easier to understand than more esoteric control schema.

Most finger pressure sensors function by placing a force-sensing device on the finger pad. These pads use various techniques to sense pressure including resistance, capacitive, and piezoelectric methods [1,2] . However almost all of these sensors are designed to be integrated into gloves for application [3]. While gloves provide a simple solution to mounting sensors and an ease of use they can often be bulky and encumbering, interfering with object manipulation. More significantly though, they cover the finger pad of the user which is the primary source of the hand's tactile sensation. By covering the pad, many tasks, notably ones requiring fine motor skills and proprioception, are severely diminished [4]. More recent research has focused on developing smaller and less intrusive finger pad sensors that stick to the finger rather than applied through a glove, however, the separation between the finger and the surface being interacted with remains. The purpose of this paper is to explore an alternative approach to the task of finger pressure sensing, by examining and designing a fingernail-based solution.

The benefit of fingernail-based sensing is that it avoids the inhibition of human haptic sensation. The finger pad on the volar side of the hand remains free to manipulate objects and engage with the environment in a natural fashion. The finger force is measured indirectly by monitoring the evolving HSV (Hue, Saturation, Value) values of a dynamically acquired digital image of the fingernail that can then be characteristically related to the pressure exerted by the nail [5,6]. This is different from previously designed fingernail sensors which use monochrome light, as examining the full color spectrum allows for clearer and more easily differentiated pressure states. This means that no barrier is placed between the finger pad and the material being interacted with, maintaining normal tactile sensation and fine-motor abilities [7]. This paper will begin by analyzing the anatomical principals that cause finger color change under finger loading. It will then analyze the relationship between HSV values and pressure using both non-localized image processing and image processing localized on different portions of the finger. Finally, it will propose a design for one such sensor that could be constructed for further study.

2. Background

2.1 Fingernail Coloration

When a finger is pressed against a surface the overall blood flow within the nail is affected – resulting in a visible change in finger coloration. This change in coloration is distinctly non-uniform. A white band develops near the tip of the finger while blood pooling in the rear of the finger develops a red hue.

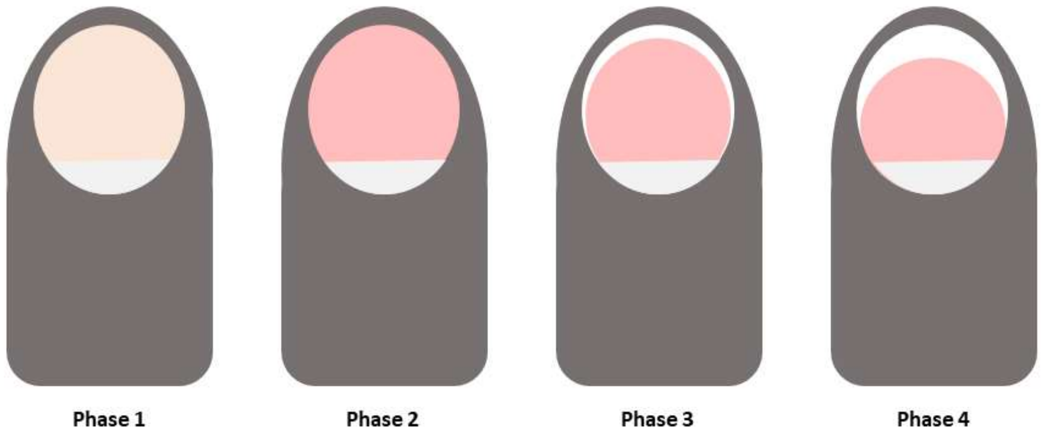

Figure 1: Changes in fingernail coloration as pressure is increased. Phase 1 shows a non-pressed normal finger that turns red as pressure in increased in phase 2. Phase 3 and 4 show the white band developing in step 3 until it reached maximum size in phase 4.

While the exact force threshold for the color changing to take place varies depending on the person, Mascaro characterized the coloration into 4 main steps [4]. First, when no pressure is applied to the finger, the finger maintains normal function and there is a uniform color across the nail. When small forces are applied, the entire finger begins to redden due to relative obstruction of venous drainage of blood from the finger to the body. Further increasing the force results in constriction of the arterial supply of blood to the fingertip, pushing the blood out of the fingertip and towards the rear of the finger. This results in the development of a white band at the distal tip of the fingernail. This band grows until a specific force limit, which varies from person to person, is reached where further increases in force have no noticeable effect on the coloration.

A human's natural finger press will easily and reliably transition through all four coloration phases without significant conscious effort by the subject. Therefore, this mechanism of discoloration is suitable for visually measuring a finger press as the fingernail transition between these phases when applying forces around 1-4 N.

2.2 HSV Coordinates

HSV is a representation of colors most often used in computer graphical programs. An alternative to the commonly known RGB model, HSV uses three cylindrical coordinates that scale from 0-255 mapped to a color cylinder to comprehensively define the color of a single pixel in an image [8]. The first of these values is the hue, defined by the angular dimension across the color cylinder. The color begins at 0 degrees with red and then wraps a full 360 degrees to become red again. The hue is then normalized to range from 0-255 for easier computer processing. The second factor is the color saturation, visualized by the radial dimension of the color cylinder. The lower the saturation the less vibrant the color appears due to a higher presence of grey in the pixel. The final coordinate is the value defined by the height axis of the cylinder. The value represents the brightness of the color with a higher value representing a brighter color, with 255 being pure white.

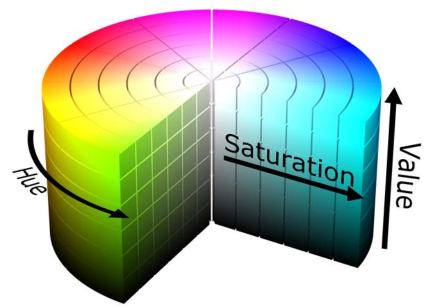

Figure 2: HSV cylinder showing the three different axis that can affect the color. The Hue, Saturation, and Value axis all affect the resulting color changing the colors hue, portion of grey, and brightness.

The benefit of examining fingernail color change in HSV rather than RGB or other similar color space representations is that HSV allows for mathematical separation of hue and intensity which the RGB system, representing colors in the amount of red, green, and blue in each color, cannot convey. This creates a more discriminating scale that can be easily interpreted for each of the three defined dimensions. Additionally, since a major characteristic of the fingernail color change at the distal tip of the finger is a transition from red to white, the fact the value coordinate specifically represents the amount of white in each image pixel is significant.

3. Experimental Design

In order to formally characterize the relationship between fingernail coloration and pressure, a simple experiment was designed. A pressure sensitive resistor secured to a table was placed underneath the finger to dynamically sense when the finger is pressed. This sensor signal is used as reference. A small camera was placed 1cm above a subject's finger with a stable light source established above the camera to capture images of the nailbed. Each volunteer subject was instructed to place a finger on top of the table mounted pressure sensor below the camera and to press down and release three times. A video of the fingertip was recorded using a raspberry pi and the HSV values of the image were simultaneously collected with the pressure applied by the subject through their fingertip. In order to collect a representative data set, this procedure was repeated 10 times for 5 different subjects.

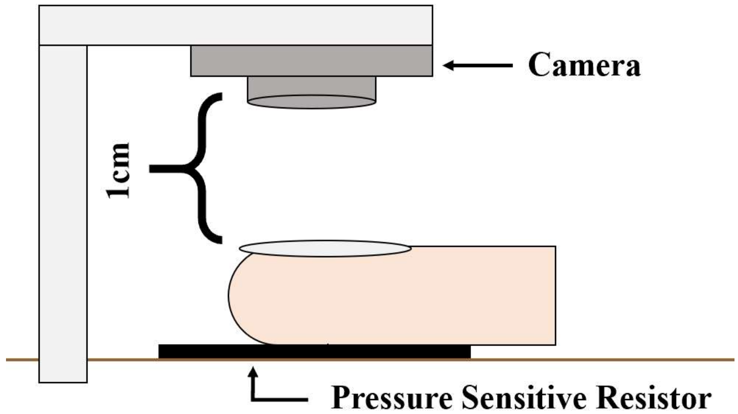

Figure 3: Experimental setup. A finger is placed 1cm below a camera and on top of a pressure sensitive resistor. This entire setup is under a consistent desk lamp and plugged into a raspberry pi for data collection.

Collection of the HSV values of the finger images included recording three different data sets simultaneously. The first set of data were the non-localized, mean HSV values. This is where the entire image was processed pixel by pixel; and the mean HSV value for the entire image was calculated. In an attempt to better characterize the physical coloration change while ignoring changing in background, two additional sets of localized data were collected. One focused on the proximal portion of the finger where blood pools and one focused on the distal tip of the finger where the white band develops, as seen in Figure 4. For these tests, the HSV values of pixels inside the selected rectangles were averaged to find the mean values in those locations.

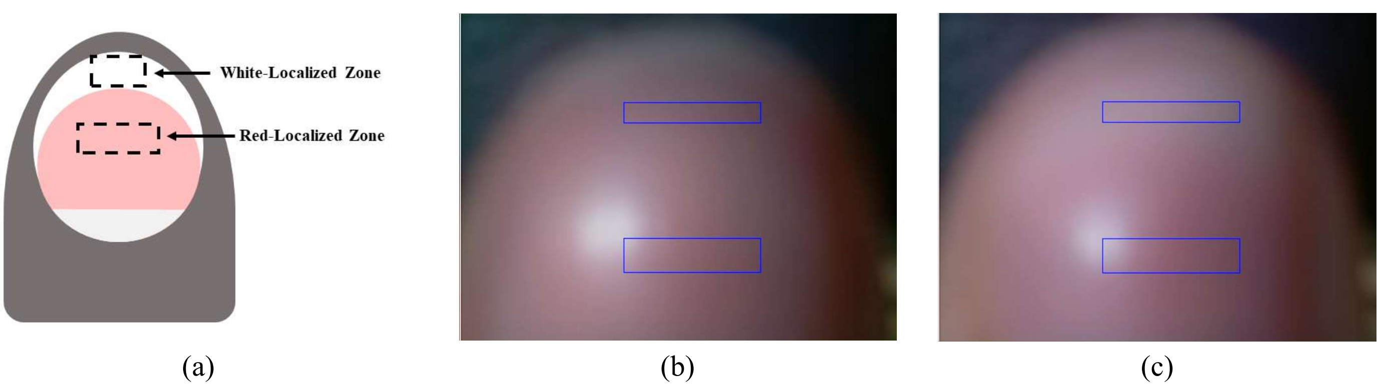

Figure 4: Locations of the regions analyzed for this study. (a) shows a theoretical ideal while (b) and (c) show these locations in a trial for not-pressed and pressed respectively.

4. Results and Data Analysis

Initially the HSV values of each trial were depicted graphically to qualitatively examine the difference between the pressed and released states.

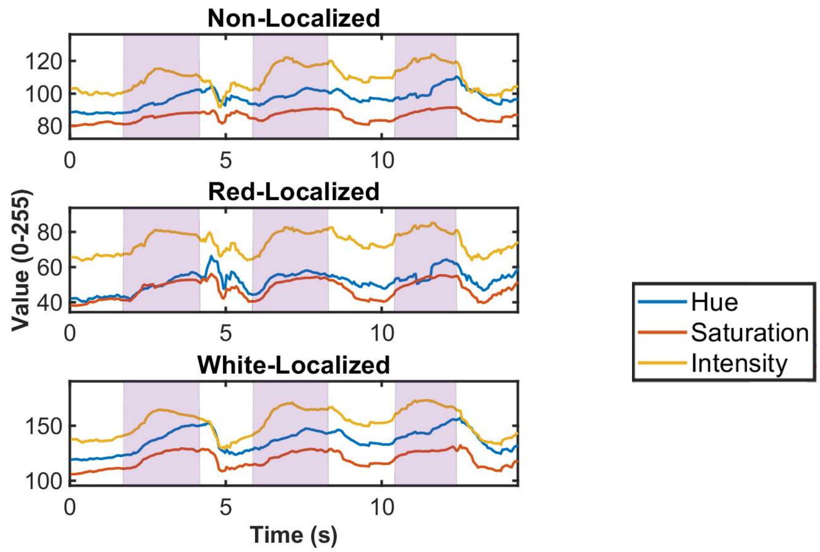

Figure 5: Representative data of subject 1 pressing and releasing the finger three times. The purple locations show the time when the finger was pressed and the increase in hue, saturation, and value values can be seen.

Observation of the graphed data reveals that downward pressure applied by the finger correlates with an increase in hue, saturation, and value of the image, which reverses once pressure is released. The results also suggest a time delay between the change in finger state and the change in coloration – likely caused by the time needed to block or restore blood flow to the finger. Additionally, the results demonstrate variability of the red-localized data. Unlike the non-localized and white-localized results, the red portion of the finger values are significantly more variable. This observation is confirmed when examining the variance of the steady states for all three methods.

Table 1: Mean variance of steady state values for the different localizations of data across all subjects. While non-localized and white-localized generally maintain low variance, the red-localized data (bold) shows high instability and the highest across all subjects.

	Subject 1	**Subject 2**	**Subject 3**	**Subject 4**	**Subject 5**
Non-Localized Variance	13.73	7.96	39.61	15.85	15.73
Red Variance	**49.19**	**28.37**	**57.36**	**31.70**	**34.52**
White Variance	15.07	16.34	39.10	26.04	20.32

The distinct difference between the variance for the red-localized dataset and the other two methods of data collection was noted in all subjects. The difference demonstrates a higher level of variability in the red-localized readings and suggests that measurement of only the red portion of the finger is likely not sufficient to be fully reproducible.

From the raw data, the HSV values measured in the pressed and not-pressed states were averaged to find the steady state value for each trial. These trials were averaged for each subject to find the overall mean and error for each location. Student-t tests were performed to determine the statistical significance of the difference between not-pressed and pressed, the results are shown in figure 6.

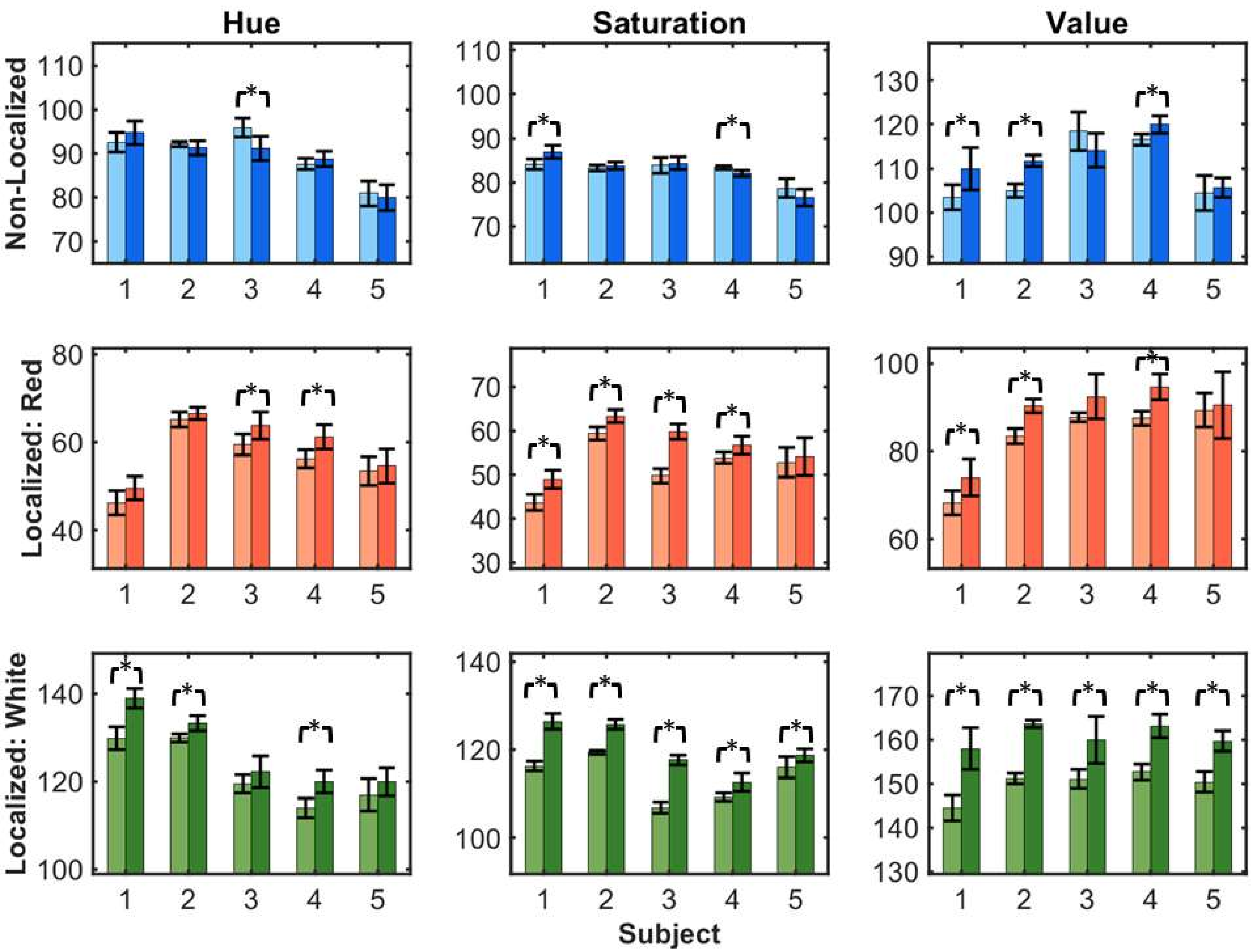

Figure 6: Mean not-pressed and pressed values for each localized position, HSV value, and subject. Statistical significance is notated using the * symbol. The statistically significant increase in values for white-localized results is evident. However, the non-localized and red-localized results show less consistent and non-statistically significant results.

In this data, all the previously mentioned trends remain evident. The increase in all HSV values from not-pressed to pressed is noticeable for most data sets and the higher variance in the red-localized results is seen by the large uncertainty values.

From this data, the benefit of distal white-localized zone analysis is evident. The difference between not-pressed and pressed is a consistent increase, particularly when comparing saturation and value, with only two subjects displaying non-statistically significant changes in hue. Meanwhile HSV values for the proximal red zone and non-localized data sets across subjects present inconclusive data. Finally, the results suggest favoring saturation and value data more than hue data. This is not only due to the overall difference between not-pressed and pressed being greater , but also because the values themselves are more consistent across test subjects. Overall, the results of this experiment reveal that for an optimal visual fingernail-based pressure sensor, the camera should only examine difference in saturation and value for pressed and not-pressed states localized to the white zone in the distal tip of the finger.

5. Sensor Design

5.1 Programmatic Design

Using these results a simple sensor was designed for subject 1. In this sensor, thresholds of saturation and value were selected based upon prior test results of 120 and 150 respectively. A simple program was constructed that reported that the finger was pressed if both the saturation and value were above the selected threshold amounts. The sensors readings were then compared to the simultaneously recorded pressure sensitive resistor to examine the sensors accuracy and precision. This test was performed for 15 presses at a time under stable lighting conditions and with a solid backdrop. The results of this comparison can be seen in Figure 7.

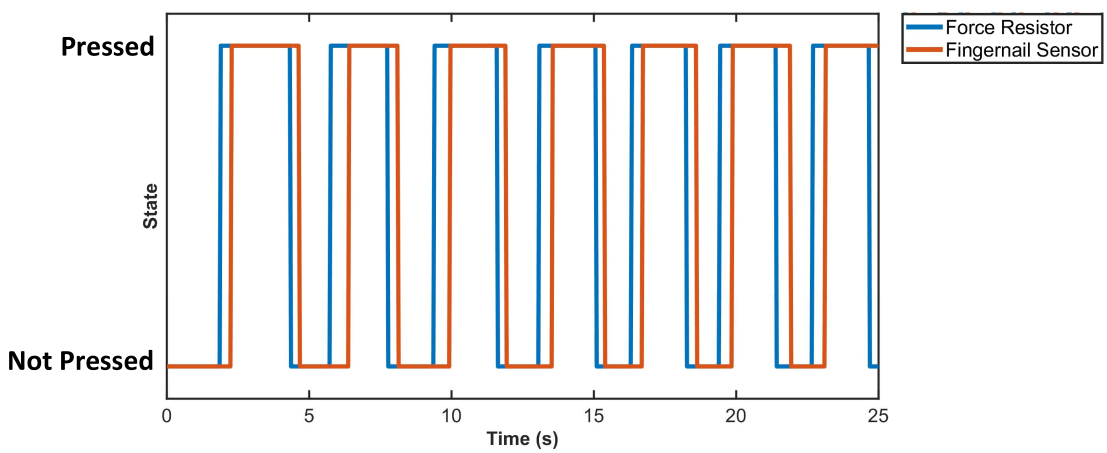

Figure 7: Pressed state for pressure sensitive resistor and designed fingernail sensor. Both sensors accurately detected finger presses, however a time lag between the resistor and fingernail sensor can be clearly seen.

The overall accuracy of the sensor was high with all 15 pressed trials being correctly identified. However, a time lag between the finger press and color change is evident and was consistent, with a measured mean of 0.41±0.03 seconds. The time lag could be reduced by lowering the thresholds for triggering; however, this increases the likelihood of false positive readings. More complex control methods, notably differential control, may help minimize these delays and further study is needed. Additionally, examination into the direct relationship between coloration and pressure value, rather than a toggle, is also needed.

5.2 Mechanical Design

One current major limitation of this application is the reliance on a stable camera position and stable lighting relative to the fingernail. For this reason, a simple mounting device for potential application was designed. The device contains a single LED light and a small raspberry pi camera held at a fixed distance (1cm) over the fingernail. From there the cables are run over the top of the hand to a raspberry pi mounted to the subject's wrist. The device is small and lightweight and is intended to be directly fixed to the fingernail using store bought fingernail glue, commonly used to glue artificial nails.

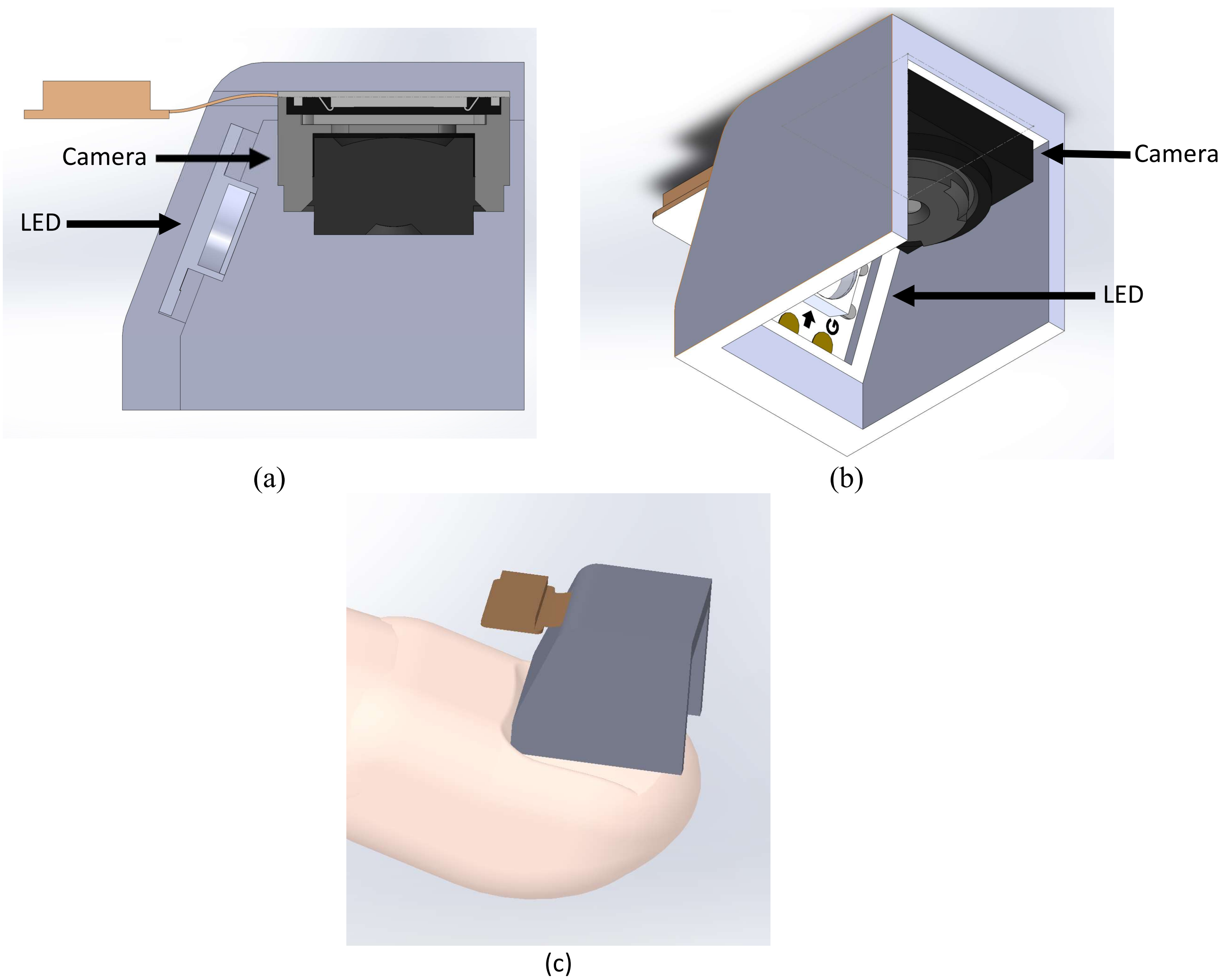

Figure 8: Proposed device design. A raspberry pi camera and LED are mounted to a small frame that is glued to a fingernail. (a) shows a crosssection while (b) shows the 3D view and (c) shows the mounting location on a index finger.

This is just one theatrical design for a mounting device and it, along with other possible designs, still need to be tested. Specifically removing the camera lens or replacing it to create a smaller focal length would allow for the overall height of the device to be reduced. This is would help minimize the sensors impact on a user and is an avenue for further research.

6. Conclusion

With the increased reliance on robotic applications there is a growing need for new methods of human control and interaction with these systems. This paper outlines the theory and design of one such controller that focuses on detecting pressure applied by a finger pressing down on a surface through detection of changes in coloration of the fingernail. This sensor style allows for finger-based control input without inhibiting a user's tactile sensation, distinguishing it from other finger pressure sensors. Therefore, this sensor could be preferentially used in scenarios where tactile and fine motor skills may be critical.

This paper first analyzes the effect that pressing a finger down has on the HSV (Hue, Saturation, and Value) values dynamically measured through a video of the fingernail. A general increase in all values can be seen in conjunction with applied pressure at the fingertip. Due to the underlying mechanism of nail color change, enhanced discrimination of this increase can be observed in specific portions of the nail rather than the entire image. Examination of both the proximal portion of the nail where blood pools and the distal portion of the nail where the white band develops revealed that the most stable and reproducible data was found by examining the Saturation and Value segments of the white band development. In order to utilize these results, a simple sensor was prototyped and tested. While the prototype accurately detected fingers being pressed, the time lag between the actual press and the trigger threshold was measurable. Finally, the design for a prototypical sensor was proposed.

Further study is needed into the limitation of such a sensor. Trials with inconsistent lighting, camera motion, and subjects of different race are still needed. Additionally, alternative optical sensors, more complex image processing techniques and control methods need to be tested. Despite these limitations, this paper supports the feasibility of utilizing fingernail sensing for robotic control.

7. References

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