Capacitive Sensing 3D-printed Wristband for Enriched Hand Gesture Recognition

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ABSTRACT

In this work, we design a wearable-form hand gesture recognition system using capacitive sensing technique. Our proposed system includes a 3D printed wristband, capacitive sensors arrays in a flexible circuit board, a low-cost micro-controller unit and wireless communication module (BLE). In particular, the wristband manipulates the changes in capacitance from multiple capacitive sensors to recognize and detect users' hand gestures. The software stack translates the detected gestures into control command for application layer, together with an user-friendly web interface that supports both data communication and training between the wristband and the host PC. We also release an open API of our designed system for future applications. Lastly, we envision our system open API will be available for developers to customize vast range of hand gesture and integrate the wristband into various applications, from command on remote computer to video game controller.

Keywords

capacitive sensing; hand gesture recognition; 3D-printed wearable

1. INTRODUCTION

As human-computer-interaction experience evolves and IoT get smarter, consumers tend to prefer a more intuitive way to interact with computers other than just tapping or swiping on their smart-devices. Thus, more and more big names have joined the playground of voice or gesture control technology. Among these interesting trend, hand gesture recognition have been researched and manufactured in various forms of wearable devices such as wristband, gloves, and rings. The techniques behind those utilize wide range usage of sensors (e.g. motion [5], camera-based sensor [24], and etc.) or the measurement the signatures of human body such as impedance or muscle electrical signal, so called electromyography (EMG) [17].

While various manufactures and researches have been in the field for long time, each of them have to face up with a different numbers of drawbacks that make them modestly adopted universal. The drawbacks include (1) the need of easy to access and replicate the already published research, (2) the convenient and friendly UI for user experience, and (3) the high cost of the some commercial or DIY systems. Existing techniques have had their own pros and cons in which some of the stated drawbacks have been solved but not all. The ultimate aim for each products should lie on optimizing system in order to satisfy user experiences and open-source DIY devices for wide range of applications.

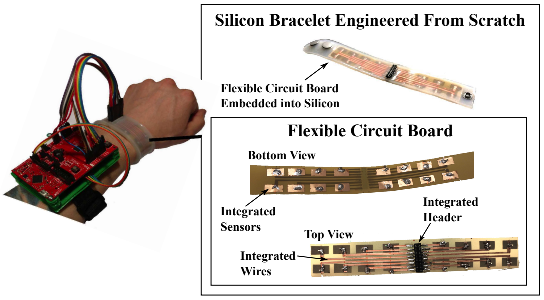

Figure 1: **Overview of the proposed system**

In this work, we introduce a hand gesture recognition system consisting of a capacitive-sensing-based wristband to sense the users' hand movement, a low-cost micro-controller to record and manipulate measured data from sensors, a BLE component to communicate with application client and a software stack to train hand gesture patterns and export control command to application layer. There are many challenges in realizing such a system. First of all, the sensitivity of capacitive sensors makes the sensor reading fluctuate over time and be susceptible to noise. Second, the design sensors (i.e. number and arrangement of sensors, distance to users' skin) must be aligned precisely. Too short distance leads to near-identical readings for different gestures, and too far distance results in low resolution of measurement. Third, real-time communication is needed to determine users' current gesture.

To address these challenges, we design a 3D printed wristband model with a complete system stack, and exploit support vector machine (SVM) method to differentiate the hand gestures. We make the following contributions in this work:

- Providing a system which includes both hardware and software designs with low-cost hardware components and open-source software stack for developers.
- Customizing sensor board design and layout using flexible circuit for precise measurement of sensor signal.
- Designing a capacitive sensing wristband and prototyping the flexible version by using 3D-printed molds.

In the following sections, we first present the fundamentals of capacitive sensing technique in Section 2. In Section 3 and Section 4, we describe in details the architecture, hardware design, and

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software stack of our proposed technique respectively. We provide the role of support vector machines in recognizing different trained gestures, and also present the application implementation based on our API. We conclude the paper with a discussion of related work and a summary.

2. CAPACITIVE SENSING BACKGROUND

Nowadays, capacitive sensing have become more and more pervasive, which has the wide range of presence, from daily life tools (control board buttons, car door handle and so on) to enormous use in smart phone touchscreen; and various application from touch recognition, proximity sensor to user identification and authentication [22, 12, 7]. In this section, we present the key principle of capacitive sensing technique. The capacitance change from sensor is usually measured indirectly from the changing in voltage, current, frequency or pulse width which are usually integrated into an application specific integrated circuit (ASIC). The variance in voltage, current, frequency or pulses is used to infer the sensor measurement.

In so-called ‘direct’ capacity sensing method, the key idea is to charge the capacitor from a defined current source for a known time and the voltage will be measured across the capacitor subsequently. This method needs a current source at very low and highly precise source. The next technique is to create an RC oscillator using the capacitor, and after that measures the time constant, frequency, or period. Although this method does not always generate high accurate results; it is easy and straightforward. Another method worth mentioning here is the one exploiting capacitor’s AC impedance. A sine-wave source excites the capacitance, and the capacitor’s current and voltage are measured. Nevertheless, the circuit is very complicated and experiences the highest part count. In addition, applying a charge amplifier that converts the ratio of the sensor capacitor to a reference capacitor into a voltage is also a common way for measuring of high precision, low-capacitance sensors.

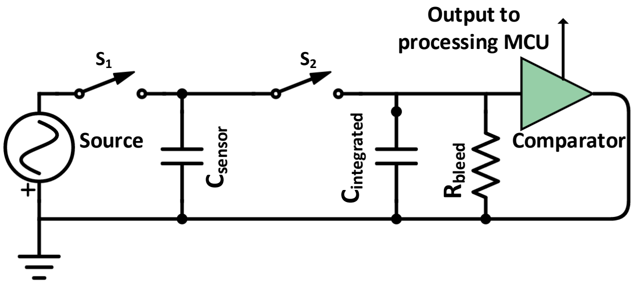


Figure 2: **Capacitive sensing under-layer circuit**

While surveying multiple capacitve sensing methods such as Microchip Capacitive Sensing Module [9], Charge Time Measurement Unit [11], Capacitive Voltage Divider [10]; Cypress CapSense Sigma Delta Modulation [4] or Silicon Labs Relaxation Oscillator [16]; we generalize the most common pattern of the underlying sensing circuit. Most common parts of the sensing circuit consist of a driving source, a sensor capacitor, an integration capacitor, a bleeding resistor and a comparator (Figure 2). The driving source is usually used to charge the sensor capacitor up to certain threshold during the closing period of switch S1. Next, the integration capacitor and bleeding resistor exist to discharge the sensor capacitor while switch S2 is closed. Finally, a comparator which is connected to ADC component of MCU will transfer the comparison of parameters observed on bleeding resistor (i.e. voltage, voltage difference or frequency changing) to process further in order to give the decision of capacitive sensor measurement.

In the open capacitor design, the sensor is considered as one side of the capacitor plate, the external contacting point will act as the second one (skin of the user in most of the cases). In our scenario, the users’ hand movement causes the compression of the silicone wristband, which lead to a change in distance from the user’s skin to the sensors and changes in capacitance.

3. SYSTEM DESIGN

3.1 System architecture

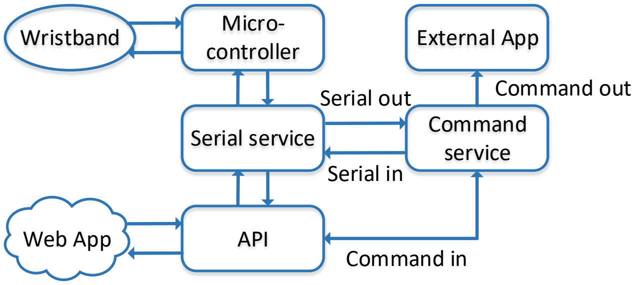


Figure 3: **Overview of the proposed system**

Our system envisions a wearable wristband that is able to determine the user’s current hand gesture, thus control external application or remote devices. The system architecture can be seen in Figure 3. Each movement of users’ hand will cause the change in capacitance which is measured from sensors on the wristband. The wristband with micro-controller unit and sensors are controlled via a wired serial connection. The micro-controller receives the single-byte command from the host device and processes one of the following action: *response connection checking*, *update baseline measurements* of all capacitive sensors, *collect data from sensors* and *transfer to host device*. The host device then processes the streamed data based on two modes: training gesture or consuming gesture events. The training gesture process takes the input capacitive measurement from the sensors, and then extract its features using SVM technique. We implement a web interface to make the training process more friendly to user while the key classification algorithm is run in the background server of the web app. Then, the recognized gesture will be consumed and translated to corresponding actions for specific applications (e.g. gestures can be translated into key presses in Linux operating system). Figure 3 illustrates the overview of our system.

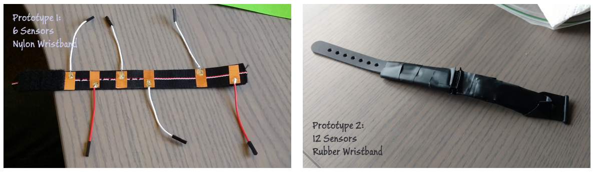
To provide a robust working prototype, the following components are carefully designed and tested:

- Silicone wristband created using 3D-printed molds.
- Custom sensor design and layout using flexible circuit board.
- Micro-controller serial communication protocol to stream sensor readings.
- Host application and API leveraging machine learning to determine gestures from raw sensor readings.
- Client application using web technologies to present a clean UI for device management and remote control via gestures.

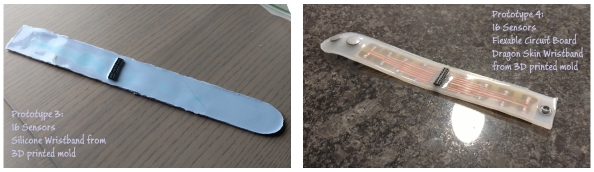
In the following subsection, we will present the design of above components more in details.

3.2 Hardware design

3D printed wristband mold. To adapt a wristband that is user-friendly and satisfy the sensitivity of the capacitive sensors, we have tried multiple combination of materials and number of sensors. Each later version boosts improvement of sensor reading resolution by increasing of numbers of sensors and reduce noise due to the interaction of the different materials with users' skin. Figure 4 shows the evolution stages of the wristband design. The mold of the wristband is designed as shown in figure 5a in order to hold the flexible circuit inside concretely. The molds is created using 3D printer and filled with silicone. After that, the copper sensors are placed inside the mold before allowing the silicone to settle.



(a) **Nylon band** (b) **Rubber band**

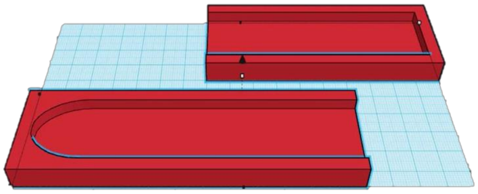


(c) **Silicon band** (d) **Dragon skin band**

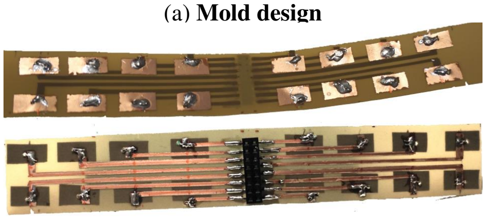
Figure 4: **The evolution of wristband design**

Flexible circuit sensor board. With the design goal of highly sensitive, compact, unobtrusive for better user experience; and based on the given measurement of normal human wristband, the wristband is designed to hold up to sixteen sensors which are placed as eight pairs. This is the maximum number of sensors that we reach at the moment to fit in the size of human wrist. The more number of sensors using, the more noise and interference between sensors and wiring will be introduced. With eight pairs of sensor in place, embedded wiring and ribbon cables are designed in parallel and compactly for requirement of highly sensitivity but still sparse enough to also minimize the noise (Figure 6). Furthermore, the whole flexible circuit is dipped into Ferric Chloride solution for the purpose of etching and removing unwanted copper from the circuit board, which drastically reduces the effect of wiring and crosstalk interference.

Micro-controller unit (MCU) and BLE module. A specialized MCU is required to measure very small and highly sensitive changes in capacitance (approximately 100μF). We found that the Texas Instrument MSP430FR5969 [20], an ultra-low-power MCU, is fit to our needs. This MCU comes with low price and variety of supports including launch pad evaluation board and CapSense library [18] which are useful for capacitive sensor measurement and data manipulation. TI capacitive measurement method relied on relaxation oscillator technique, in which the internal ladder network is toggled due to the charge or discharge of the sensor capacitor. The frequency of oscillation [19] is related to sensor capacitance by: $f_{\text{osc}} = 1/(1.386 \times RC \times C_{\text{sensor}})$, in which RC is the value of internal RC circuit. By counting the oscillation periods over a fixed frame duration, the frequency can be calculated and the sensor capacitance can be measured. The hardware device listens incoming serial data, interprets commands following our pre-defined configuration and responses with ack messages or measurement data streaming. On top of that, two HC-05 BLE modules [6] together with a USB-TTL converter are also used as an alternative and unobtrusive way to stream measurement data to host device.



(a) **Mold design**



(b) **Flexible circuit board**

Figure 5: **3D printed mold to hold the sensor board**

In the next section, we will present a software stack to augment all the hardware components together and also will provide examples working applications that we implemented.

4. IMPLEMENTATION

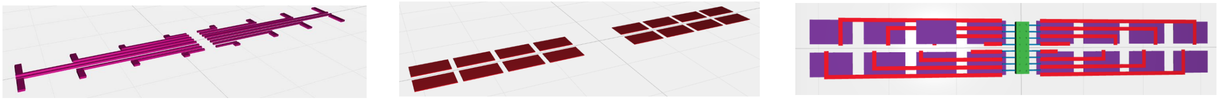
4.1 Software stack

The flow-chart of our software stack is presented in Figure 7. With the concrete design of hardware components, our software on the host device, which include multiple application layers, are implemented to (1) communicate with hardware on wristband, (2) receive streaming measurement data, (3) train and recognize gesture, and (4) translate gesture into specific consuming actions.

The host computer communicates with hardware on wristband via two-way serial communication. The host application, based on command line interface (CLI), searches for available serial ports, creates connections, and communicates with the wristband. Currently, the hardware is configured with the capability of responding to different flags from host computer, including *echo*, *update baseline*, *train* and *stop* commands. Echo command is used by the host to check if the wristband connection is still alive and ready to communicate. Update baseline command instructs the wristband to take new baseline measurements of all capacitive sensors with the given iteration parameter. This request blocks all other commands until baselining is complete. Train command allows the host device to collect data for a specific gesture with the input amount of measurement. When this command is received the wristband will flash a light to inform the user collection is about to begin. The user should perform the gesture and press a button to begin training. Finally, stop command halts measurement and put the hardware into an idle state.

Support vector machine (SVM). SVM is a binary linear classifier [1] represented by a decision boundary which is determined by the hyperplane constructed from sums of a kernel function: $d(x) = \sum_{x_k \in Y} \alpha_k t_k K(x, x_k) + b$ where t_k is the target output of +1 or -1, b is a bias parameter, Y is a set of support vectors. The support vectors x_k corresponding to weight $_k$ are obtained by a quadratic optimization and satisfy the condition $\sum_{x_k \in Y} \alpha_k t_k = 0$, and $x_k > 0$.

Given a data set, SVM can find the best separating hyperplane that maximizes the margin between the positive and negative classes. The kernel function $K(.)$ is designed so that it can perform a nonlinear mapping from an input space into a higher dimensional space.



(a) **Wiring** (b) **Sensor placement** (c) **Combine with header**

Figure 6: **Design of wiring and sensor placement with wire header**

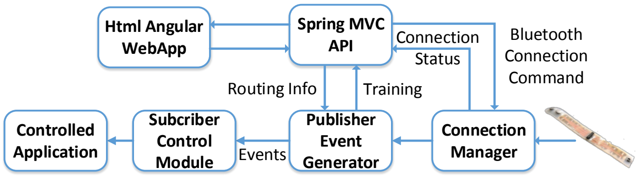
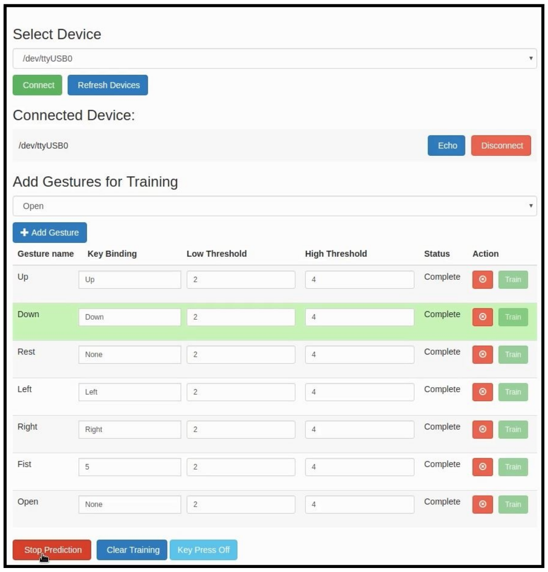


Figure 7: **Flow diagram of software layer**



Select Device

/dev/ttyUSB0

Connected Device:

/dev/ttyUSB0

Add Gestures for Training

Open

Gesture name	Key Binding	Low Threshold	High Threshold	Status	Action
Up	Up	2	4	Complete	⊗ Train
Down	Down	2	4	Complete	⊗ Train
Rest	None	2	4	Complete	⊗ Train
Left	Left	2	4	Complete	⊗ Train
Right	Right	2	4	Complete	⊗ Train
Fist	5	2	4	Complete	⊗ Train
Open	None	2	4	Complete	⊗ Train

Figure 8: **The Web User Interface for Training Different User's Gestures**

The output of $K(.)$ is an inner product of two vectors in kernel feature space which is important for SVM learning. As we consider gesture recognition is a multi-class problem, our training technique is a binary classifier. Therefore, we only need to extend it to multi-class SVM. Generally, we can build binary classifiers which distinguish between one of the classes and the rest (one-versus-rest). The classification of a new sample for the one-versus-rest case is done by taking the class that has the largest positive distance.

In this paper, we apply the radial basis kernel functions for SVM classifier for hand gesture training because gesture recognition from noisy sensor reading requires a training process. With the knowledge of SVM, incoming data stream from hardware on wristband is received and converted to a proper format that can be used for training process. Trained and recognized gestures are managed by a web application that utilizes websockets for real-time communication (Figure 8. Currently pre-configured gesture set includes basic hand gestures: up, down, left, right, open palm and fist.

4.2 Implemented application

Current web application interface provides a core set of gestures, but can be easily customized to add more if needed. Each gesture thresholds can be tweaked in order to fit with the needed accuracy. Therefore, users and developers can add and customize different gestures, which is not limited to the six existed ones. The interface is simple and intuitive and the open API is available for developers to integrate the wristband into their application. The translation from hand gesture recognition to consuming events enables wide range of integration to external applications such as controlling remote mobile devices, issuing commands to remote computer or playing games from afar. We tested our system in Tetris game as shown in Figure 9. In this scenario, when pre-configured gestures are recognized, hand gestures events are consumed and translated into corresponding key presses in Linux operating system as up, down, left, right in order to play the game smoothly.

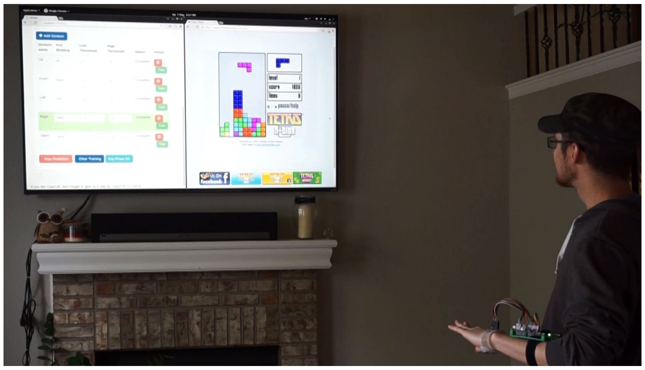


Figure 9: **An example application of our designed wristband**

5. RELATED WORKS

Sensor and gesture recognition with wearable devices. There are multiple researches on wearable sensor devices from MIT Media Lab such as Wristque [8] in which the wearable wristband consists multiple sensors such as localization sensor, motion sensor, light and humidity sensor; or the electromagnetic field detector bracelet [21] that senses the distance to the monitor display. Popular hand gestures that have been and recognized in previous researches can be classified as (1) realizing whole palm movement (fist, stretch, left, right), (2) counting number of fingers (thumbs, pointing fingers), and (3) configuration of open and close fingers (pinch gesture). These gesture can be recognized by measuring and calibrating data from outer skin source or inner skin source. Outer skin source measurements include the using of camera [15], attaching magnetic sensor or accelerometers and gyroscope to user's wrist and finger [2], or collecting the contour of the moving wrist [3]. On the other hand, inner skin source method measures the muscle signal (EMG), i.e. Myo product [17]; or the impedance tomography (tomo [25] and tomo2 [26]).

Enriched gesture recognition. Based on previous hand gesture recognition methods, enriched gesture recognition is the next target with the aim for more precise and accurate detection for the bigger set of gestures. By exploiting capacitive sensing mechanism of touchscreen, [23] can estimate the pitch and yaw of the finger related to the touchscreen. Tomo shows the results of five hand-pinch gestures and eight whole-hand gesture with the high accuracy while using the device on wrist or arm. TypingRing [13] is a ring-like device allowing user to type on any surface so that input text from a group of 3 letters using 3 consecutive fingers.

Capacitive sensing based gesture recognition. The most relevant to our work consists of capacitive-sensor-based wearable devices. GestureWrist [14] utilized capacitive measurement of wrist-shape changes and forearm movement with the usage of a system with 6 receiver electrodes. The key technique here is to utilize the measurement of capacitance changes between those 6 receiver electrodes and 1 transmitter electrode on the top of the users' wrist. This is different from what we proposed here since we measure the capacitance changes of capacitors which are formed by electrodes as 1 plate and human skin as the second plate. Furthermore, the GestureWrist is limited to the small number of capacitive sensors and not open to the consuming events for recognized gesture in application layer.

6. CONCLUSION

In this paper, we proposed a hand gesture recognition system utilizing capacitive sensing technique. We presented a 3D printed wristband-form device augmented sensor arrays under the flexible circuit board. We also provided a detail hardware and software interface of the proposed system. We envision that this technology can be easily integrated into a smart wristband or a smartwatch through an implemented application (Tetris game). More importantly, we would like to emphasize that our proposed technique can also be used for remote control aid (Presentation, Drone controllers, etc.) or assistance on game play devices among other applications.

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