Wearable Capacitive-based Wrist-worn Gesture Sensing System

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***Abstract*— Gesture control plays an increasingly significant role in modern human-machine interactions. This paper presents an innovative method of gesture recognition using flexible capacitive pressure sensor attached on user's wrist towards computer vision and connecting senses on fingers. The method is based on the pressure variations around the wrist when the gesture changes. Flexible and ultrathin capacitive pressure sensors are deployed to capture the pressure variations. The embedding of sensors on a flexible substrate and obtain the relevant capacitance require a reliable approach based on a microcontroller to measure a small change of capacitive sensor. This paper is addressing these challenges, collect and process the measured capacitance values through a developed programming on LabVIEW to reconstruct the gesture on computer. Compared to the conventional approaches, the wrist-worn sensing method offerings a low-cost, lightweight and wearable prototype on the user's body. The experimental result shows that the potentiality and benefits of this approach and confirms that accuracy and number of recognizable gestures can be improved by increasing number of sensor.**

Keywords*— *Gesture recognition, Capacitive pressure sensor, Capacitance measurement, Wearable electronics.

I. INTRODUCTION

Gesture interface between human and machines has been a centre of attention in past decades due to the rapid growth of the market, as well as growing scientific interest. Such communications are implemented through wearable and flexible devices which offer great advantages over conventional rigid electronics, such as lightweight, bendable, portable, and potentially foldable devices.

The general approach of sensing gesture can mainly be classified into two categories: (1) movement-sensor-based and (2) camera-based [1]. In the movement-sensor-based gesture recognition, sensors attached to user's body measure any movement and motion [2]. For example, flexible sensors for measure the bending of finger or accelerometer that measures the movement of hand are using movement-sensor-based approach. Studying these motions, will enable the computer/machine to reconstruct various gestures. On the other hand, camera-based gesture recognition has been recently developed as a commonly used method for the computer vision application [1] [2]. The computer is able to extract the gesture information though images

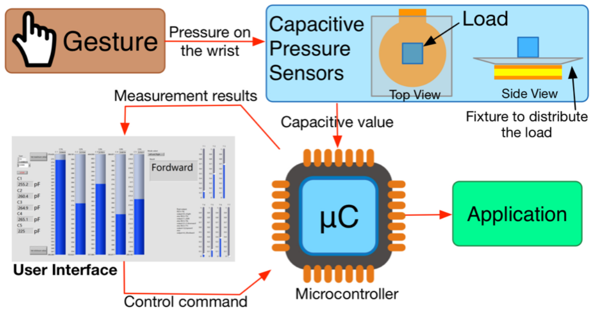

Fig. 1. System structure

processing. For example, Microsoft Kinect, a developable 3D camera, is able to collect the gesture information including position (x, y, z coordinate), palm tilt, angle of fingers, etc. This approach is widely applied on game consoles and some high-tech platforms, which obviously improves the users' experiences [2].

The movement-sensor-based solution is low cost, wearable and portable. The disadvantage is that this method requires a lot of attachments, such as flexible sensors, on the user's body. The camera-based solution provides a higher accuracy and better user experience. However, since the camera is fixed, the operational range space is limited [2].

This paper aims to introduce a trade-off approach of gesture recognition methods that requires less attachments and has no limitation from camera. The gesture is reconstructed on the computer to perform the corresponding control by measuring the pressures around the wrist. The recent advances in flexible and wearable electronic s and materials allow this kind of device to be in form of a wristband [3] [4].

This paper is organised as follows: The working principle and system structure is introduced in Section II. Section III presents a method for the measurement of a small change in capacitance. The hardware and software design are provided in detail in Section IV and V respectively. Finally, the experimental result and conclusion of the prototype will be discussed.

II. METHODOLOGY AND SYSTEM DESCRIPTION

The tendons movements around the wrist due to gesture changing is the working principle behind the sensing mechanism [5] [6] [7]. Attaching a certain number of pressure sensors around the wrist, capture the pressure variations distribution from the sensors output. These variations are used to distinguish and reconstruct gestures on computer after calibration [6] [8] [9].

To achieve that, this project introduces a system based on flexible and thin capacitive pressure sensors, measuring readout circuit, flexible substrate wristband and user interface software.

The system structure is shown in Fig. 1. Initially, the changes in pressure distribution stem from changes in gesture are captured by capacitive pressure sensor array. The sensors used in this design are five flexible off-the-shelf sensors (SingleTact). Besides, a microcontroller is used to measure the capacitance value by charging them and count the time steps one by one [10]. Finally, the capacitance values will be used to reconstruct gesture according to the pre-recorded values in calibration step. The user interface on the computer aims to display the value and do some configurations, which may be not necessary in real application scenario. In this way, the gesture can be used to control some devices such as smart phone.

The flexible and accurate capacitive sensors with 0.35 mm thickness, have been embedded on a PDMS based flexible and transparent substrate. The key characteristics of the sensors summarized as Table 1 [11].

Table 1. Key parameter of the sensor

Typical Baseline Capacitance (C_{sen})	230 pF
Typical Capacitance Change (ΔC)	5.5 pF
Force Range	0-4.5N

Since the range of capacitive change is small, the capacitance meter in the system is crucial for gesture recognition. In this paper, we use a microcontroller to generate pulse to charge the capacitors and count the time [12]. The microcontroller should have a good performance in terms of 1) fast system clock to control the changing, 2) small input leakage current to minimize the effect of unwanted charging and 3) the amount of analogue input pins.

Fig. 2 shows the peripheral circuit of the microcontroller. Two digital pins and one analogue input pin are employed to measure one capacitor. In addition, an integrating capacitor is needed to share the charging during each measured period. The value of this capacitor (C_{int}) depends on the C_{sen} and $\triangle C$ of the capacitive sensor. Theoretically, it should be much larger than C_{sen}. The larger the C_{int}, the better the precision, but slower the sampling rate [12].

There are four steps for one capacitor measurement:

1) Discharge: Set all digital pins to low level and give it a delay to discharge the C_{int} and C_{sen}.

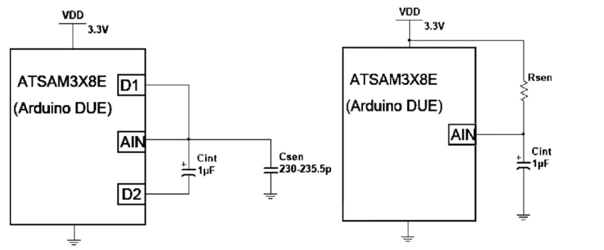

Fig. 2. (left) Capacitance measurement circuit including the microcontroller and one capacitive sensor. (right) Equivallent circuit of the (left) under the rapidly charging and sharing

2) Charging: Set D1 to high level (V_{DD}) and D2 to high-impendence with a short delay to disconnect the C_{int} and fully charge the C_{sen}.

3) Sharing: Set D1 to high-impendence and D2 to low level with a short delay. The C_{int} is now connected so that it is able to drop current from D2 and share the charge with C_{sen}. The V_{int} will be slightly increased. At the same time, increase the time counter (k++).

4) Comparing: Read the voltage on the AIN. If V_{int} reaches an upper reference voltage V_{RH} (here we take V_{RH}=0.7V_{DD}), stop charging and sharing and store the counter value. Otherwise go back to step 2.

5) Calculation: Calculate the capacitance by counter k, C_{int}, V_{DD} and V_{RH}.

In this case, the equivalent circuit is shown in Fig. 3. The D1, D2 and C_{sen} can be considered as a resistor since:

$$I_2 = \frac{Q_2}{T_{Sw}} \approx (V_{sen} - V_{int})C_{sen}/T_{sw}$$

Therefore:

$$R_{sen} \approx T_{sw}/C_{sen}$$

Where T_{sw} is the switching period.

As can be seen in Fig. 2(right), the equivalent circuit is a RC circuit. Therefore, during the charging and sharing, the V_{int} will exponentially reach V_{RH}. Equation (1) shows the relationship between the current 'k' value and V_{int}.

$$V_{int} = V_{DD}(1 - \mathrm{e}^{-(\mathrm{k}T_{sw})/(T_{sw}/C_{sen})}) \quad (1)$$

Once the V_{int} reaches V_{RH}:

$$V_{RH} = V_{DD}(1 - \mathrm{e}^{-(\mathrm{k}T_{sw})/(T_{sw}/C_{sen})})$$

$$C_{sen} = \frac{\ln{(V_{DD}/(V_{DD}-V_{RH}))}}{k/C_{int}} \quad (2)$$

As can be seen in Equation (2), the C_{int}, V_{DD} and V_{RH} are constant and k is the measured value so that the C_{sen} can be calculated [12]. It is worth noting that the C_{sen} is not the actual value of the capacitive sensor. It consists of the capacitive sensor and parasitic capacitance (C_{par}) introduced by the circuit and microcontroller, which can be removed by offsetting a certain value of C_{par} in testing stage [12]. However, it would not influence the result since the $\triangle C$ is the main variable indicating the change in force and the C_{par} is a constant.

The waveform on AIN during one measuring period is shown in Fig. 3(a). A zoom in is shown in Fig. 3(b). Where the circuit parameters are:

Table 2. Circuit parameters in this experiment

Parameter	Value	Parameter	Value
V_{DD}	3.3V	V_{RH}	2.27V
$C_{par(measured)}$	15 pF	C_{sen}	230-235.5pF
C_{int}	1 μF		

In this paper, there are five capacitive sensors need to be measured. To achieve multiple capacitors measurement, the general idea is that apply the same procedure one by one, which means duplicating the components and circuit five time and using a 'for' loop to switch in the program. However, this method requires three pins including one analogue pin for each sensor. Furthermore, it is time-consuming to operate multiple ports.

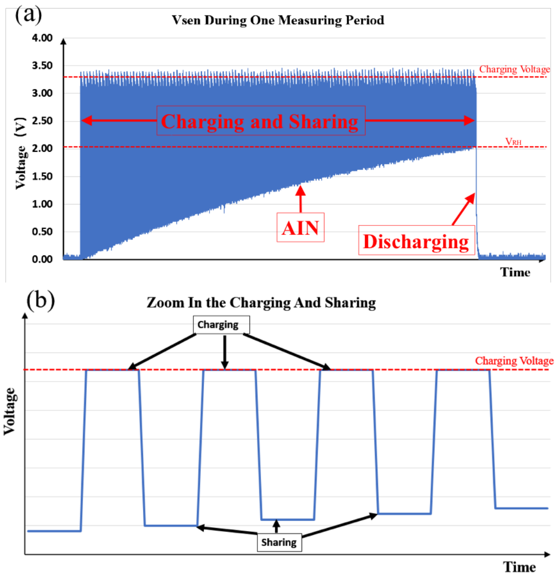

Fig. 3. The V_{sen} waveform during a complete measuring period captured by an oscilloscope is shown in (a). Ideally, (b), showing the effect of each charging and sharing on V_{sen}, can be seen by zooming in (a).

Fig. 5 shows an alternative approach where the five sensors sharing common D1, D2 and AIN. On another port of C_{sen}s, they are connected to digital IO (S1, S2 and S3) instead of ground. By switching the DIO between low level and high-impendence to select the sensor. When one sensor is selected, the corresponding DIO should be in low level while the others are in high-impendence mode to prevent them from drawing current to influence the selected sensor. This approach requires a small input leakage current of these DIO. Otherwise, all capacitors would be charged simultaneously and it equivalently is a set of parallel capacitors.

III. Design and Programming

A. Microcontroller Programming

The programming of the microcontroller (ATSAM3X8E) is on Arduino compiler. However, the Arduino library should not be used because the high-speed operation is essential, especially in sharing and charging stages. Operating the register directly will significantly improve the performance.

In the program design, firstly, a 'for' loop is used to switch the measured sensor, followed by the charging and sharing loop to wait for the V_{RH}, which is the crucial part:

```
while (ai < 2815) {
    Charge();
    Share_Charge();
    k++;
    ai = analogReadADC();
  }
Discharge();
  Serial.print(str[i]);
  Serial.print(k);
  k = 0;
  delay(2);
```

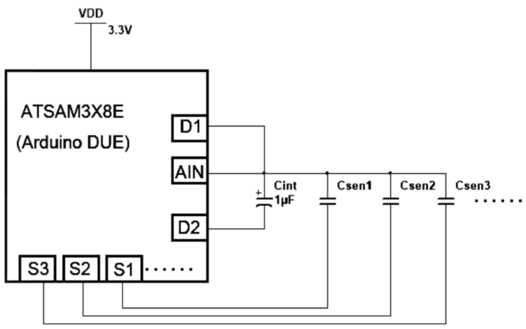

Fig. 4. Multiple capacitive sensors measurement

After that, all capacitors in the circuit should be discharged and the 'k' value, together with the sensor index symbol, will be sent to the software by serial communication.

B. User Interface Design

The software is developed on LabVIEW platform. A producer/consumer structure is used to receive the 'k' data and process it. Five capacitance values are displayed on the front panel. In calibration step, the capacitance value of each gesture will be stored. After that, the pre-recorded gesture can be recognized. The amount of recognizable gesture increases as the amount of capacitive sensor.

C. Wristband design

The wristband design is also important for overall performance and repeatability. The aims of the wristband design are to:

1) ensure the sensors are attached on the user's wrist appropriately,
2) isolate the capacitance introduced by the user's body,
3) offer a mechanical support to the sensors.

The Polydimethylsiloxane (PDMS) is chosen as the main body of the wristband because it is flexible, inert, low-cost and commercially available [13]. The sensors are embedded in the PDMS as flexible substrate to helping the sensors in attach the body. The wristband design and its configurations is shown in Fig. 5.

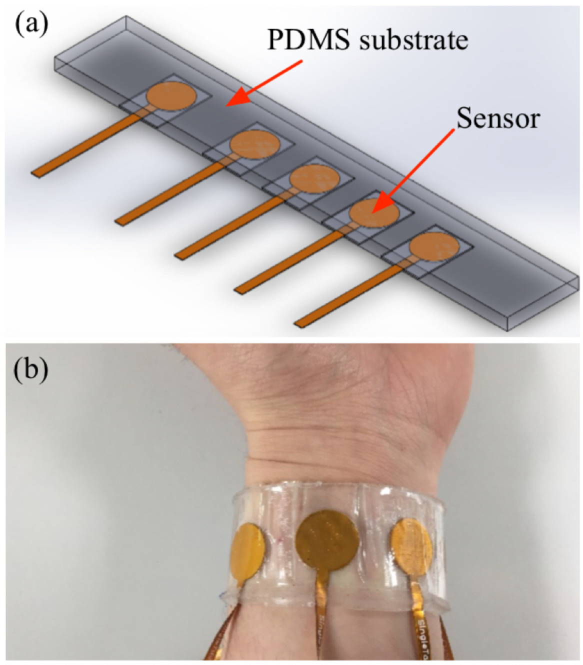

Fig. 5. (a) is the 3D model of the wristband with five embedded sensors. A prototype is shown in (b).

IV. Experimental Result

Experiment was carried out in terms of the precision of capacitance measurement, sampling rate and the number of recognizable gesture, with the first prototype of wearable gesture sensing wristband.

Under the same circuit parameter as Fig. 4, the error in terms of change in capacitance can be kept within 0.3 pF at static state. When the sensor is attached on body, this number is raised to 0.7 pF due to the sphygmus, small hand movement etc.

Additionally, the sampling rate is around 25Hz. According the Equation (2), a larger C_{int} can improve the precision but reduce the sampling rate. The result shows that, at this parameter, the precision and sampling rate are acceptable for real-time on-body gesture recognition.

The number of recognizable gesture is limited by the number of sensors and measuring precision. For example, single sensor is able to measure the open and close of the hand only. As regards five sensors, the maximum number is around six (Fig. 6). If more than that, the judging condition between gestures would be mixed up and the recognition rate will dramatically reduce. As shown in Fig. 7, when the gesture is changed, a clear difference on the capacitance values can be distinguished.

V. Conclusion

This paper aims to propose a wearable capacitive-based gesture sensing system. The prototype has been implemented by innovative capacitive-based pressure sensing using flexible sensors embedding in flexible PDMS layer. It realizes the majority of the functions and has a good potentiality to be a wearable product. The future work will involve fabrication of in-house flexible pressure sensors and replace the off-the-shelf sensors to improve the performance. Further improvement will be achieved by miniaturising the readout circuits [14, 15] and applying machine learning for gesture classification.

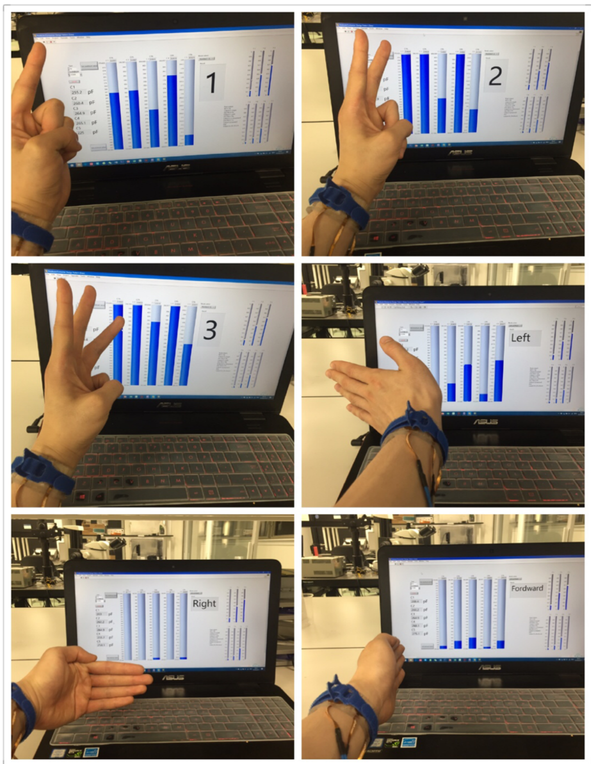

Fig. 6. Gestures and the corresponding capacitance values (bar charts).

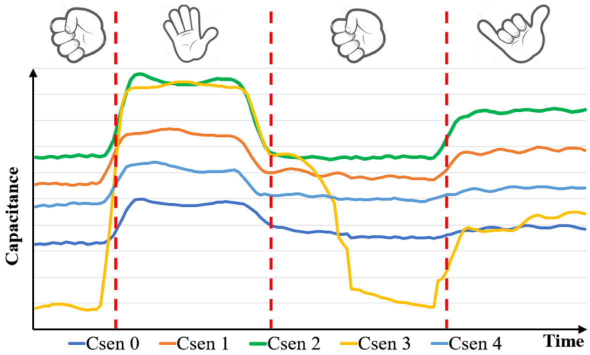

Fig. 7. The change in gesture results in the capacitances variations over time.

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