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# *E-wear: A Low-cost, Long-lasting, Multi-sensor Integrated Smart Clothing for Human Motion Tracking*

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***Abstract.*** Human motion tracking is essential in fields such as rehabilitation medicine, sports training, human behavior analysis, and film and game production. However, existing methods face significant limitations: inertial measurement units (IMUs) are prone to accuracy issues and magnetic field interference, RGB cameras capture only 2D images and rely heavily on image algorithms, and optical flow sensors, while accurate, are prohibitively expensive and highly sensitive to environmental factors. These challenges underscore the need for a low-cost, high-speed, comfortable, and highly integrated motion measurement system. In this paper, we introduce E-wear, a smart clothing solution that integrates multiple sensors to provide a low-cost, long-lasting, and reliable system for human motion tracking. 8 fabric strain sensor and 1 IMU sensor are used to measure 9 joint motions. The system demonstrates high sensitivity in fabric sensors, robust performance after washing cycles, and provides accurate real-time motion data.

***Keywords:*** Smart clothes, Fabric sensor, Human Motion Tracking, Wearable

## 1. Introduction

Nowadays, human motion tracking plays an increasing important role in rehabilitation medicine, sports training, human behavior analysis, and film and game production. Some commercial devices have been used to collect human motion information.

These devices can mainly be divided into several types: RGB camera, Optical flow sensor, Inertial Measurement Unit (IMU) wearable device. For visual methods (RGB camera), efficient image processing algorithms are required, as they typically can only generate 2D human models and are susceptible to external environmental influences such as lighting; Optical methods require measurement in a fixed environment, with high measurement accuracy, but the system cost is expensive; IMU based sensors can be worn on the body and are suitable for long-term data acquisition, but they are susceptible to magnetic field interference, and has poor wearing comfort.

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(a) RGB camera (b) optical flow sensors (c) IMU

Figure 1. Different motion tracking techniques

Compared to non-wearable devices, wearable devices have broader development prospects in the field of human motion information collection. However, developing low-cost, comfortable, and highly integrated wearable motion measurement systems remains a significant challenge [1]. We have designed a motion capture system for clothing integration and named it 'E-wear’. The system adopts a fusion sensing technology based on fabric strain sensors and IMU sensors to achieve fast and real-time collection of human motion data.

The remainder of this paper is organized as follows: Section 2 presents the methodology, Section 3 describes the human pose estimation algorithm, Section 4 discusses the results, and Section 5 provides conclusions.

## 2. Methodology

### 2.1. Principle

As shown in Fig.2, the proposed device is composed of 8 fabric strain sensors and 1 IMU sensor, and a signal acquisition circuit used to process data from all sensors and send it to the computer via Bluetooth. We used three different types of conductive yarns for manufacturing sensors, circuit wiring, and connecting wires to the motherboard. Strain sensors are used to measure the main and sub-joints (shoulder, hip, elbow and knee joints), while the IMU sensor is used to measure root joints (body trunk).

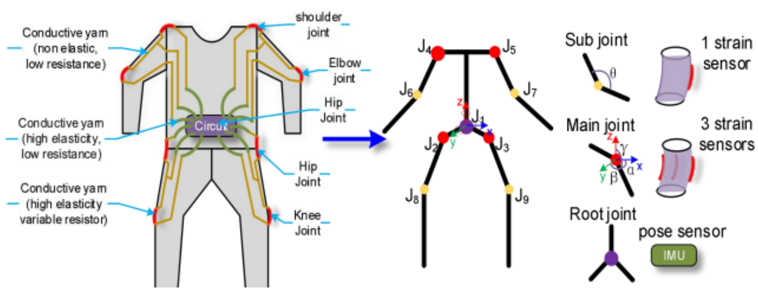


Figure 2. E-wear motion tracking system

### 2.2. Material

Here, we use three type yarns to build the sensor and circuit. Yarn I (high resistivity and high elasticity) is chosen to fabricate the strain sensor. Yarn II (medium resistivity and non-elastic) is for signal wire. Yarn III (low resistivity and high elasticity) is for circuit board connector. The conductive yarn samples are given in Fig.3.

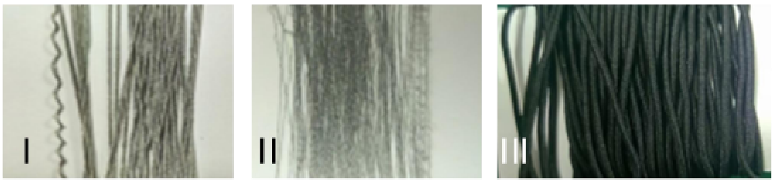


Figure 3. Conductive yarn

The physical properties are shown in Tab.1. The resistivity of Yarn I, II and III are 80, 30 and 8 ohm/m, respectively. And their diameters are 0.8, 0.3, 1.2 mm. Yarn I has high resistivity, it is helpful to increase the sensitivity of the strain sensor. Yarn II and III have low resistivity, which can reduce the signal loss.

Table 1. Parameters of the conductive yarn

| Yarn | Resistivity | diameter | Material |
|---|---|---|---|
| I | 80 ohm/m | 0.8 mm | Nylon/silver fiber |
| II | 30 ohm/m | 0.3 mm | Cotton/silver fiber |
| III | 8 ohm/m | 1.2 mm | Cotton/silver fiber |

### 2.3. Fabrication

We use a digital sewing method to manufacture the strain sensor and circuit wire on clothes [2]. As shown in Fig.4, the strain sensor is made into a loop shape to achieve maximum tensile effect in the length direction. The digital sewing machine uses flat stitch to achieve the routing of sensors. The circuit wire is made into an S shape to avoid affecting the stretching of the fabric. The manufacturing of circuit wire adopts a Zigzag stitch; this routing method can effectively reduce the wire resistance.

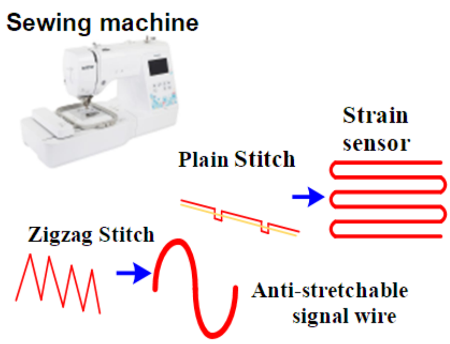


Figure 4. Fabrication of the strain sensor and circuit wires

### 2.4. Model

#### 2.4.1. Strain sensor model

In this work, we use fabric strain sensor [3] to measure the bending of the joints. A fabric strain sensor is a resistive type stretching sensor. As shown in Fig.5, when the strain sensor is stretched, its resistance will increase. So, we can measure the tensile deformation by measuring the change of the resistance.

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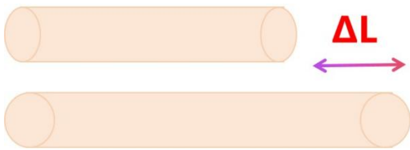


Figure 5. Working principle of the strain sensor

The resistance equation of the strain sensor is given as,

$$DR = \rho \frac{\Delta L}{S_0} \tag{1}$$

where, ΔR is the change of the resistance; and ρ represents the resistivity, and $s_0$ is the cross-section area of the resistor; ΔL is the elongation of the resistor.

### 2.4.2. 2D joint model

Here, Constant Curvature Equation (CCE) is used to construct the 2D joint model. When a joint bends, the arc of the joint will become longer. According to CCE, the bending angle of the joint can be calculated.


Figure 6. Working principle of the strain sensor

The Constant Curvature Equation is given as:

$$D\theta = \frac{\Delta L}{r} \tag{2}$$

where r is the equivalent radius of joint, and Δθ is joint's bending angle [4].

### 2.4.3. 3D joint model

As shown in Fig.2, the main joints, i.e., shoulder and hip joints can achieve 3D bending. However, the 2D joint model can only describe the bending of joints in a 2D plane. So, we present a 3D joint model [4] (Fig.7), which is a cylinder, and its bending angle in 3D space can be measured by using three strain sensors [4].

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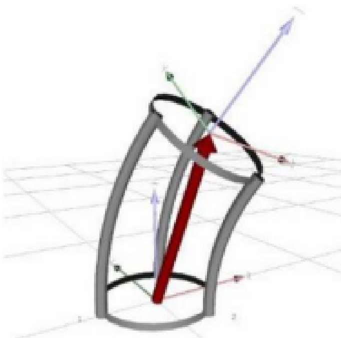

Figure 7. Geometric model and coordinates of the 3D joint mode

Using the lengths measurements $l_1$, $l_2$ and $l_3$ for this cylinder, the geometric parameters r, θ and φ can be reconstructed [5]. We first introduce two intermediate parameters which correspond to mean length, and the irregularity between individual lengths,

$$\bar{l} = \frac{l_1+l_2+l_3}{3} \tag{3}$$

$$g = \sqrt{l_1^2 + l_2^2 + l_3^2 - (l_1 l_2 + l_1 l_3 + l_2 l_3)} \tag{4}$$

Then the geometric parameters can be computed by the following equations [2],

$$\theta = \frac{2g}{3b} \tag{5}$$

$$\mathbb{r} = \frac{\bar{l}}{\theta} \tag{6}$$

$$\varphi = actan(\frac{\sqrt{3}(l_3-l_2}{(l_3+l_2-2l_1} ) \tag{7}$$

## 3. Human pose estimation

We have designed a human pose fusion perception strategy based on IMU and fabric sensors. The estimation of human pose is calculated using input data from the IMU (three-dimensional angle) and 8 strain sensors (resistance values). The algorithm is given in Tab.2.

Table 2. Pseudo code of the human skeleton pose algorithm

| 1. Initializes the Biological parameters of skeleton parameters | r_joint,bones |
|---|---|
| 2. Obtain the data from IMU and strain sentor | IMU_angle,R1~R8 |
| 3. Calculate the streching of strain sentor | Eq.(1) |
| 4. Calculate the joint bending angle | Eq.(2) |
| 5. Update root joint J1 | IMU_angle |
| 6. Update father joint J4,J5,J2,J3 | 02,03,04,05,IMU_angle,B2,B3,B4,B5 |
| 7. Update children joint J6,J7,J8,J9 | 06,07,08,09,02,03,04,05,IMU_angle,B46,B57,B28,B39 |
| 8. Update the end of skeleton | 06,07,08,09,02,03,04,05,IMU_angle,B6,B7,B8,B9 |
| 9. Draw the coordinates of all the joints | |

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Here, we measured the skeletal biological information, includes the equivalent radius of 8 joints and the length of 12 bones. The data are given in Tab.3 and Tab.4.

Table 3. Radius of the joint

| Joint | J6 | J7 | J8 | J9 | J2 | J3 | J4 | J5 |
|---|---|---|---|---|---|---|---|---|
| Radius | 7 | 7 | 3.5 | 3.5 | 11 | 11 | 6 | 6 |

Table 4. Bone's length

| B4 | B5 | B46 | B57 | B6 | B7 | B12 | B13 | B28 | B39 | B8 | B9 | B1 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 14 | 14 | 23 | 23 | 21 | 21 | 12 | 12 | 39 | 39 | 33 | 33 | 40 |

According to the human skeleton pose algorithm given in Tab.2, and the data given in Tab.3 and Tab.4, we have developed a program for human pose estimation by using MATLAB software. The codes are given in the Appendix.

## 4. Results and discussion

### 4.1. Experimental system

As shown in Fig.8, 'E-wear' human motion tracking system includes tight-fitting clothes with fabric sensors, a data acquisition circuit, and a data visualization program.

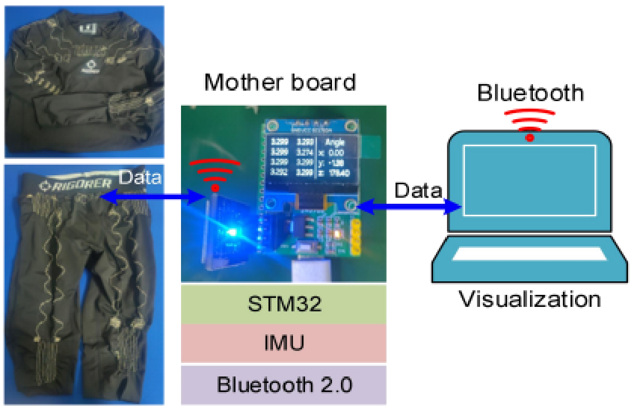


Figure 8. E-wear human motion tracing system

As discussed in Section 2.1, the sensing clothing composed 9 joint sensors. The 3D angle measurement of the root joint is achieved by IMU sensor. The main and sub joints are measured by the 2D and 3D fabric sensors.

The data acquisition board is a multi-channel resistance collector based on STM32. And the circuit also receive data from the IMU module though a serial communication port. All data is sent to the computer via Bluetooth 2.0 module.

The joint motion data are drawn into a skeleton diagram of human posture through a visualization program on the computer. This visualization program is developed based on the human pose estimation algorithm proposed in Section 3.

Fig.9 shows the proposed visualization program.

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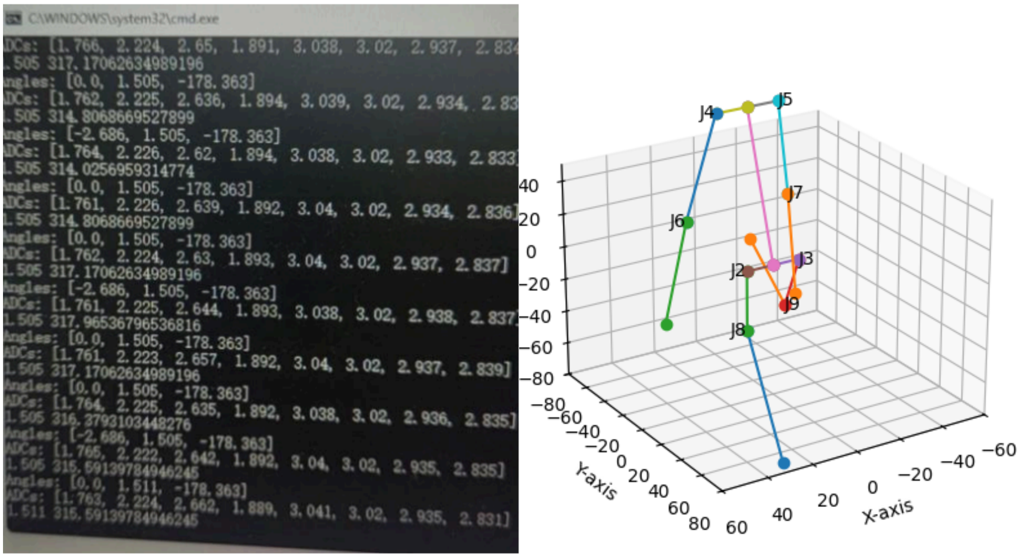


Figure 9. The visualization program

## 4.2. Results

As shown in Fig.10, we tested a fabric strain sensor integrated in the cloth. The initial resistance of the sensor is 17.4 Ω. When the elongation is 1.5 cm, the resistance change value is 4.5 Ω.

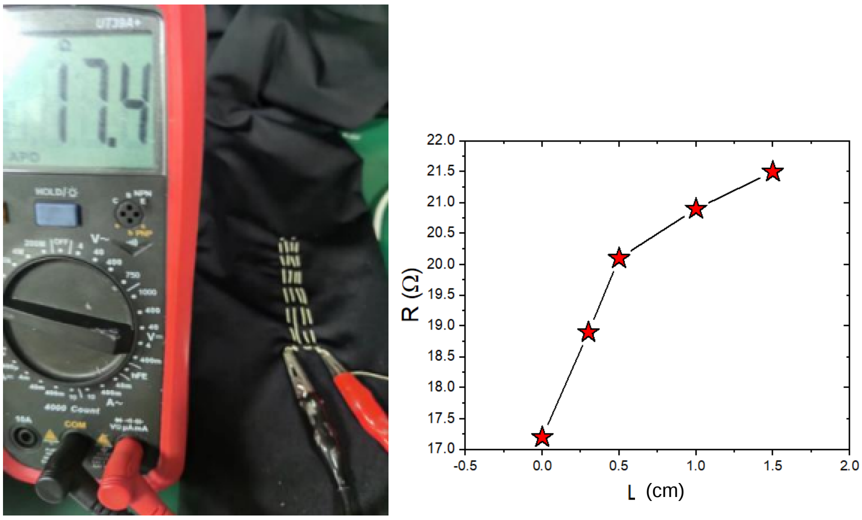


Figure 10. Fabric strain sensor stretching test

To investigate the sensing performance of the sensor, we use the definition of sensitivity, which is,

$$s = \frac{DR}{\Delta L} \tag{8}$$

where ΔR is the resistance variation, and ΔL is the elongation of the strain sensor.

According to Eq. (8), the sensitivity of the fabric strain sensor is 0.3 Ω/mm.

As wearable device, the fabric sensors integrated into clothing will face multiple wash cycles [6]. To test the performance of the strain sensor after washing, we conducted durability tests. As was tested 20 times. Its resistance value changed from 17.4 Ω to 16.8 Ω. The change rate is 3.4%.

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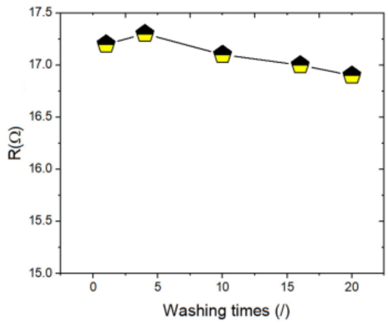


Figure 11. Fabric strain sensor washing test

The performance of the E-wear system is given in Fig.12. Our human pose estimation algorithm model can accurately calculate the angles of human joints and draw the human pose through visualization programs.

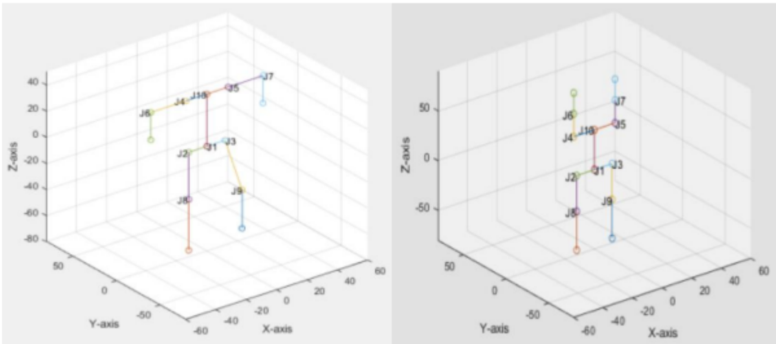


Figure 12. Visualization of human motion data

## 5. Discussion

In this section, we compared different human motion tracking method. As shown in Tab.5, our system has the advantages of high speed, wearable, and unrestricted by environmental constraints. And the total cost is 400 dollars.

Table 5. Comparison of human motion tracking technology

| Scheme | Price(RMB) | 2D/3D | Speed | Requirement | Accuracy |
|---|---|---|---|---|---|
| RGB(camera) | 5~10k | 2D | Low | Low speed target,avoid strong or weak light | Middle |
| Light(Vicon) | 100~200k | 3D | High | Indoor,fixed | High |
| IMU | 20~30k | 3D | Middle | Avoid magnetic interference | Low |
| Fabric strain sensor | 3k | 3D | High | -- | Middle |

So, E-wear system is highly suitable for outdoor motion capture, medical rehabilitation, and high-level sports training.

## 6. Conclusion

During experimentation with E-wear, it was observed that it responds accurately and quickly to changes, making it an ideal tool for capturing human motion. Additionally, its responsiveness suggests potential applications as a novel human-computer interface. The main contributions of:

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Design of an intelligent fabric sensor that can be integrated into clothing.

Development of a human pose estimation algorithm based on the fusion of strain sensors and IMU sensors.

In the near future, E-wear could serve as a method for capturing user input in virtual reality (VR) and mixed reality (MR) environments.

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