Stretchable Tactile and Bio-potential Sensors for Human-Machine Interaction: A Review

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Abstract. Human machine interaction (HMI) technologies have been widely applied to the fields of the complicated task assignment, biological health monitoring, prosthesis techniques, and clinical medicine. In this paper, different kinds of HMI modes are reviewed, such as tactile sensors, biological sensors, and multi-sensory data. Stretchable electronics integrated with multi-function sensors on the polydimethylsiloxane (PDMS) substrate are laminated onto the skin surface for collecting temperature, strain, pressure, biological signals simultaneously. More conformable and natural human-machine interaction methods would be realized, which will provide effective ways for human-robot interaction similar to human-to-human interaction, and finally drive the development of the coexisting-cooperative-cognitive robot (Tri-Co Robot) technology.

Keywords: Human machine interaction · Flexible/stretchable electronics Tactile sensor · Biopotential sensor · Multi-sensory data

1 Introduction

Human machine interaction (HMI) is the field to study the information interaction between robots and humans, where the motion of the robots is controlled by the signals from human [1]. Conventional rigid sensor based on silicon wafer would lead to discomfort to body when it is laminated onto the skin surface. Flexible and stretchable electronics are the development direction for HMI [2, 3]. It is very important for the flexible and stretchable electronics to be designed with stretchability to satisfy the deformation of the soft skin and to control the robot more conveniently [4, 5].

The schematic graph for the human to communicate or interact with robots or machines is shown in Fig. 1. The HMI modes can be divided into several categories: (i) soft tactile sensors, (ii) biological sensors, and (iii) multi-sensory data. To understand

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the development of the soft tactile sensing technologies, it is necessary to compare the four kinds of sensors: piezoelectric sensors, piezoresistive sensors, capacitive sensors, and acoustic sensors. Wang et al. designed and developed many piezoelectric materials and devices which transduce the human strain variation to the output voltage for HMI applications [2]. Bao et al. designed and fabricated an ultra-sensitive capacitive sensor array with pyramid-structured polydimethylsiloxan (PDMS) for pressure visualization [4, 6, 7]. Sound and audio systems were also widely applied to speech analysis and recognition, which are the hottest research areas [8]. Bio-potential signals from human bodies were also used to HMI application, such as, electromyography (EMG) [9, 10], electroencephalogram (EEG) [5, 11], and electrooculography (EOG) [12]. Features of the biological signals are extracted to control the motion of the external actuators. A prosthetic hand was designed to record multi-sensory data simultaneously, and data fusion methods were proposed to control the prosthesis [13].

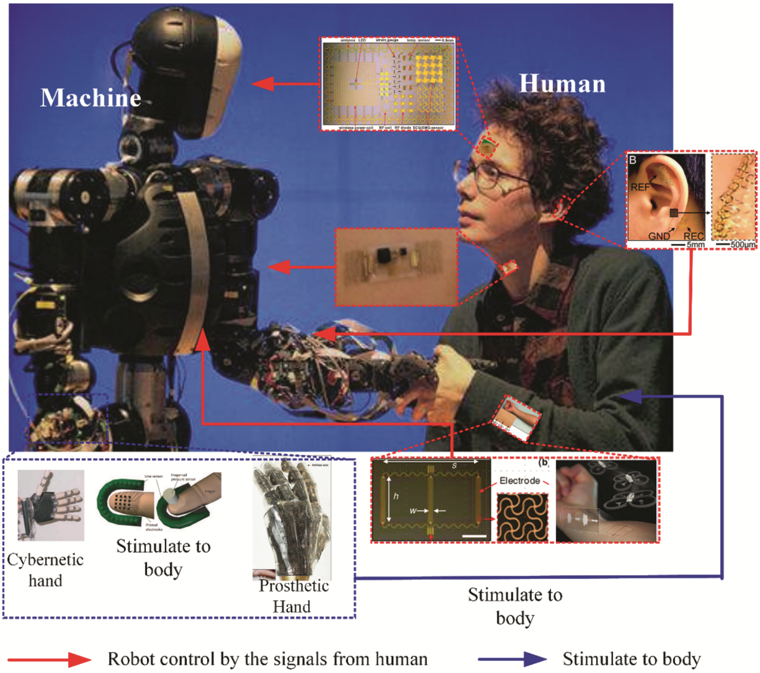

Fig. 1. Schematic graph for humans interacting with the robots

There are many review articles about the flexible and stretchable electronics which have been applied to biological healthy monitoring, electronic skin, and HMIs. Soft tactile sensors for HMI enable a generation of touch-sensitive health-care robots to attend the old and the disabled to collect human physiological signals for health monitoring [14]. However, all these reviews mainly focused on the design and development of the stretchable E-skin in different applications. The HMI modes should be also classified via the flexible and stretchable electronics. The rest of the review article is arranged as follows. In Sect. 2, soft tactile sensors are reviewed for HMI. Bio-potential signals for HMI are reviewed in Sect. 3. Multi-sensory data for HMI is introduced in Sect. 4. The whole review article is concluded in Sect. 5.

2 Tactile Sensors for HMI

It is important for the robot integrated with tactile sensors to interact with surroundings or humans for completing complicated and dynamic tasks. During the past decade, large numbers of soft tactile sensors were designed to HMI applications. As a branch of mechanical sensors, soft tactile sensors are categorized by the transduction methods, such as, piezoelectric sensors, piezoresistive sensors, capacitive sensors, and acoustic sensors.

Piezoelectricity refers to the production of electrical charging in certain materials under mechanical force due to the occurrence of electrical dipole moments [15]. This approach was used to convert mechanical stresses and vibrations into electrical signals via piezoelectric materials with high sensitivity, rapid response, and a high piezoelectric coefficient. A rapid-response flexible pressure sensor matrix which was based on the direct conversion of mechanical stress was developed to pressure visualization [16]. With external pressure applied to the flexible sensors, the sensor matrix could give the corresponding pressure distribution. Figure 2 depicted that transparent ZnO Nanowire sensor was designed for self-powered gesture recognition [17]. With the motion of different fingers, various control commands were generated to control the motion of the external actuators based on soft piezoelectricial sensors [18].

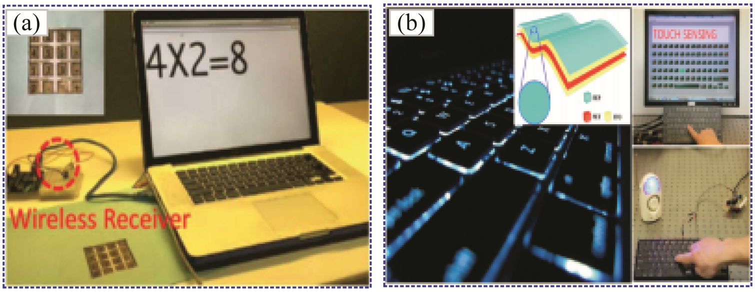

Fig. 2. HMI based on piezoelectricial sensors [17, 18]

Piezoresistive sensors enable transduction of force variations into changes in resistance which is easily detected by an electrical measuring system [19]. These sensors were widely used to detect strain information of human bodies. Stretchable silicon strain sensor integrated with serpentine structure was designed to control the motion of the external actuator as shown in Fig. 3 [20]. Piezoresistive sensors with liquid metals were encapsulated by elastomer channels for strain monitoring, which had excellent electrical and mechanical properties. Wu et al. designed a epidermal strain sensor with liquid metal for finger motion detection, and two features with the finger bending were recognized which demonstrated that the liquid metal strain sensor had the potential application in

HMI control [21]. Javey et al. developed a tactile sensing glove for capturing a variety of comprehensive hand motions, such as holding, gripping, grasping, squeezing and so on [19]. It clearly gives a promising application in the force visualization and HMI application.

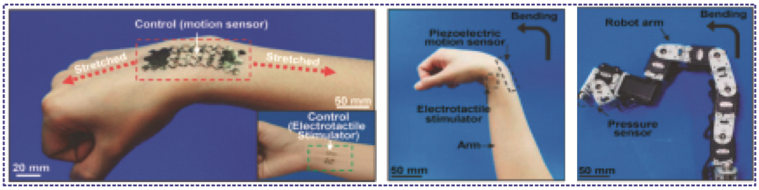

Fig. 3. HMI based on piezoresistive sensors [20]

The capacitance (C) of a parallel plate capacitor, denoted as the ability to store a charge, is described by $C = \varepsilon A/d$, where ε is the dielectric constant, and A and d are the area and the distance between the two electrodes, respectively. Figure 4 depicted that flexible, pressure-sensitive active matrix on a plastic substrate with high-pressure sensitivity and rapid response time based on microstructured rubber was designed and fabricated, which could be used to precisely map the static pressure distribution and health monitoring. Bao et al. demonstrated a transparent and stretchable capacitive sensor array based on carbon nanotube electrodes on elastic substrates that was sensitive to both pressure and strain [6]. The sensitivity of the capacitive sensor array depended on the pyramid-structured PDMS which increased the air voids between PDMS and organic semiconductor layer. When a little fly stood on the sensor, it would generate a plus signal and give pressure visualization with high sensitivity.

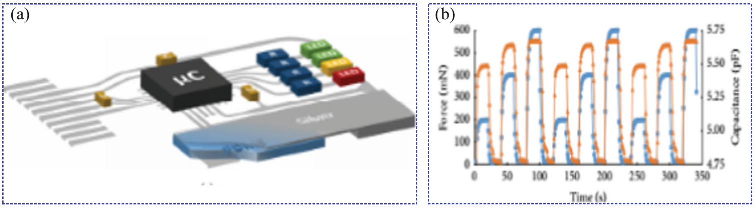

Fig. 4. HMI based on soft capacitive sensors.

The epidermal mechano-acoustic sensors were compatible to the soft curvilinear skin for capturing acoustic vibrations for local words and the speech signals, and the human voices were recognized to control the motion of the robot [22]. The mechano-acoustic vibrations were recorded while speaking “left,” “right,” “up,” and “down.” The spectrogram highlighted the unique time-frequency characteristics of each of the four words. The intimate contact between the sensors and the skin rendered their operation almost unaffected by ambient acoustic noise. These features could allow the epidermal acoustic sensor to be used for communication in loud environments by first responders, ground controllers, or security agents.

3 Bio-potential Sensors for HMI

The contraction of muscles could generate EMG signals, which were acquired by the surface EMG electrodes noninvasively [23]. The stretchable multichannel sEMG patches were designed for robot manipulation via eight gestures of the hand [24]. Combined with the large-scale size, the multichannel noninvasive HMI via stretchable μm thick sEMG patches successfully manipulated the robot hand with eight different gestures, whose precision was as high as conventional gel electrodes array. Figure 5(a) depicted the stretchable EMG electrode was designed to control the motion of mobile robot via different human gestures [9].

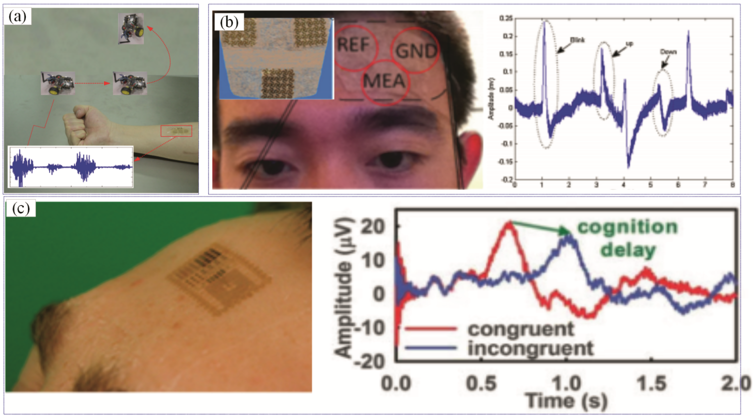

Fig. 5. HMI based on soft bio-potential sensors. (a) EMG sensor [9] (b) EOG sensor [27]; (c) EEG sensor [5].

The EOG sensor mounted on the forehead that was prepared by exfoliating the stratum corneum with tape yielded reproducible, high-quality results, as demonstrated in alpha rhythms recorded from awake subjects with their eyes closed [5, 25, 26]. The expected feature at 0–10 Hz appeared clearly in the Fourier-transformed data. This activity disappeared when the eyes were open. The EOG system for HMI applications consisted three modules: sensors for EOG recording, the signal collection instrument, and the computer control system (Fig. 5(b)) [27]. The signals were recorded by a commercial amplifier system to control the robots or computer games via different eye motion.

Brain–computer interface (BCI) technology was a radically communication option for those with neuromuscular impairments that prevent them from using conventional augmentative communication methods [5]. Current BCI recorded the EEG signal at the scalp or single-unit activity from cortex to control cursor movement, select letters or icons, or operate a neuroprosthesis [28]. The experimental setup for HMI based on EEG signals included a participant wearing the electrodes, an amplifier, an analog-to-digital converter, classifiers, and software as shown in Fig. 5(c). It was demonstrated that people played computer games with the EEG sensor for HMI application [29].

4 Multi-sensory Data for HMI

Multi-sensory data infusion methods were used to build a natural interface allowing humans to interact with robots or machines similar to human-to-human communication through speech or gestures, which required more information from both the human and machines.

A prosthetic hand integrated with artificial skin was highly compliant, and mechanically couples to the curvilinear surface of the prosthesis as shown in Fig. 6 [13]. The stacked layers highlighted the location of the embedded electronics, sensors and actuator. The thermal actuators were in fractal inspired formats to facilitate uniform heating during stretching and contraction of the skin layer. A notable increase in EMG activity for the loaded compared cases suggested an ability to detect loaded lifting. Stooping motions induced signature responses of the strain gauge, distinct from those associated with squatting [13]. In this circumstance, the temperature sensor provided a reliable indicator of muscle exertion, associated with increases in metabolic reactions and blood flow that lead to corresponding increases in skin temperature. Strain/pressure sensors positioned beneath the humidity sensors could exhibit reduced mechanical responses to external deformations.

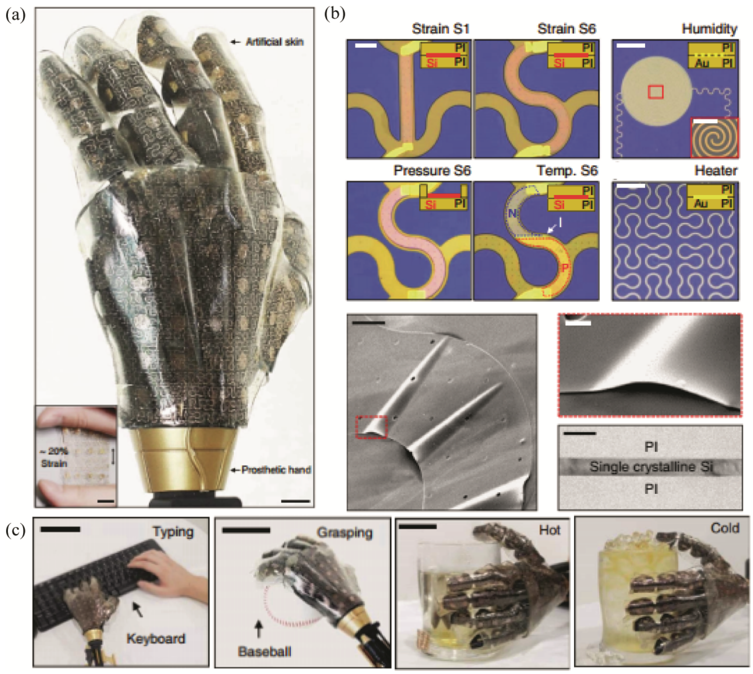

Fig. 6. HMI based on soft multi-sensory data [13].

Flexible multifunctional devices with EMG, temperature, and strain signal recording simultaneously were designed to a more practical HMI application for humans to interact with machines [30]. The temperature sensor consisted of a serpentine conductive trace (Cr/Au) with a width of 20 μm, thickness of 200 nm, and length of 26 mm in total. The strain sensor and the EMG sensor used the same metal pattered in different kinds of geometry. Together with the EMG sensor, the strain gauge, and temperature sensor, this platform offered important functionality intervention for lower back exertion.

5 Conclusion and Discussions

Robots integrated with soft sensors are also illustrated for disease treatment. Different modes of HMI are introduced, which includes tactile sensors, biological sensors, sand multi-sensory data. Soft tactile sensors for HMI will aid future development in robotics, biomedical devices, sports, automobile, textiles, and many other fields. Stretchable electronics integrated with multi-function sensors on the PDMS substrate are laminated onto the skin surface for collecting temperature, strain, pressure, and EMG signals simultaneously. Multi-source data fusion methods are adopted for the robot to accomplish the task and interact with human.

Although HMI applications have developed fast in recent years, there exist some difficult problems. (1) The production of devices with low-power consumption or self-powering ability remains a topic worthy of in-depth study, because the energy crisis is currently one of the largest challenges in our society. (2) The cost of tactile sensors is another problem for hindering the development and application in the field of service robot and health care. Low-cost materials and fabrication process for tactile and biological sensors are effective to promote HMI application.

Future HMI will also intelligently respond to variations in the external environment based on novel information transmission technology. With the rapid development of artificial intelligence technologies, intelligent HMI with smart sensing, computing and decision technologies would provide an effective way for people to interact with machines similar to human-to-human interaction.

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