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Development of sEMG Sensing Techniques for Hand Prostheses

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Abstract: In order to make prosthetic hands acting like human hands as much as possible and improve the biomimetics and intelligence, it is necessary to add multi-sensor perception system on electric prosthetic hand system. In this paper, the theory of sEMG and its signal analysis technology are introduced. SEMG sensing techniques for hand prostheses are surveyed. These sensing techniques include tactile and slip sensing, proximity sensing, cold and hot sensing, and multi-sensing fusion. Meanwhile these prosthetic hands sensors and sEMG sensing techniques are compared. Some further researches and developing trend of sEMG sensing techniques for hand prostheses are indicated.

Keywords: sEMG; tactile and slip sensing; proximity sensing; cold and hot sensing; multi-sensing fusion; hand prostheses

1 Introduction

Bionic intelligence sensing techniques for hand prostheses is much improved since artificial limb center of the former Soviet Union developed first EMG prosthetic hand [1]. The current focus is development of hand prostheses with multi-degree-of-freedom (DoFs) and intelligent sensing [2]-[9], the purpose is to improve flexibility of prosthetic hands, the inter-communication ability of environment information and autonomy of hand prostheses. After entering the 21st century, the requirement of prosthetic hands' multi-perceived information feedback is higher and higher in biomedical field and ammunition industry. Meanwhile, in order to imitate the function of human's hands and improve bionic intelligence of hand prostheses, multi-sensor system added to EMG hand prostheses has become a hotspot research.

The purpose of prosthetic hands' research is to improve self-care for amputees, narrow the functional gap between the patient and healthy person, ensure amputees mental health and enhance social morality and the development of medical industry and warfare business. Meanwhile the research of hand prostheses with multi-degree-of-freedom and intelligent sensing is a multidisciplinary field: multi-sensor technology, information fusion technology, biomedical engineering, electronic information, and so on, which promotes mutual penetration of each advanced technology. The function of human's limb system and its perceptional feedback are complex, while commercial electric prosthetic hands mainly use EMG control and don't have information perceptional feedback at present. It is necessary to add multi-sensor perceived system to EMG prosthetic hand system for the function of hand imitation and the improvement of hand prostheses' bionic intelligence.

Otto Bock, Motion Control, Liberating Technologies and Touch Bionics Inc. are representative companies in the world at present. According to the investigation of amputees [10], an ocean of amputees are unwilling to be equipped with hand prostheses on sale and most of amputees with prosthetic hands are unsatisfied[11]. The main reasons are that the function of artificial hands is

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simple, its bionic performance is dreadful and there is a large gap between prosthetic hands and real hands. Amputees dream of having a sound body. And amputees with hand prostheses wish to control the prostheses according to their own will and have function of perceptional feedback. At present and after a long time the main goal of hand prostheses research is to provide highly intelligent electric hand prostheses and bring the probability of improvement or treatment to amputees. Human hand is a bio-mechanical system with multilevel control, stimulation, and input and output channel of information reception, which can achieve various ingenious and complex action via coordinated control of nervous system. Whereas conventional prostheses use vision as feedback to estimate whether object is clenched and slipped, unlike human hand can work without vision feedback. Consequently, to make hand prostheses as same as human hand with intelligent sensing ability is becoming the front edge and hot spot of rehabilitation engineering.

Amputees with EMG hand prostheses use sEMG signals as control signals of the prostheses to achieve manipulation of natural hand movements. It involves acquisition and processing of sEMG, hand action recognition, motion control of prosthetic hands, and so on. Organic combination of multi-sensor and sEMG hand prostheses will improve bionic and intelligence of prosthetic hands. A comprehensive description of sEMG sensing techniques for hand prostheses is provided below.

2 SEMG signals

SEMG is a kind of bioelectric signal recorded and induced by electrodes when neuromuscular system is active. There exist different levels relevance between active state and functional state of sEMG and muscles, accordingly it can reflect the activities of neuromuscular to some extent. It has a great practical significance in evaluation of muscle function of rehabilitation medical research field and fatigue recognition, sports technical rationality analysis, muscle fiber type, anaerobic threshold's non-invasive prediction of sports science. The control system for powered prostheses is shown in Fig1.

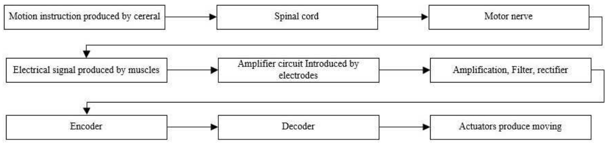

Figure 1. The control system for powered prostheses

SEMG signals are one-dimension time series, which are gained by electromyography. It is the result of sum of electrical change caused by electrodes when multiple sport units are active. And it involves the number of sport units in different function state and active function, discharge frequency, synchronization and recruitment pattern of different sport units, setting position of surface electrodes, thickness of subcutaneous fat, and body temperature changes. SEMG acquisition and processing are shown in Fig. 2. For years, the analysis of sEMG is focus on time and frequency threshold [12]. The purpose of signal analysis is to discuss the possible cause of sEMG signal change and reflect activity and function of muscles effectively by change of sEMG signals. In recent years, with people's deepening cognition to nonlinear characteristics of neuromuscular system, experts start using nonlinear mathematical methods to analyze EMG signals [13]-[14]. It means that this field steps into a new stage from then on.

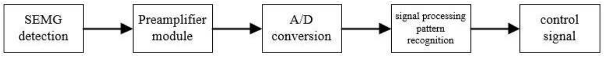

Figure 2. SEM G acquisition and processing

Commonly used time domain characteristics of the calculation method is as follows: Mean value:

$$AV = \frac{1}{N}\sum_{i=1}^{N} X_i \tag{1}$$

Standard deviation:

$$std = \sqrt{\frac{\sum_{i=1}^{N}\left(X_i - \overline{X}\right)}{N-1}} \tag{2}$$

where $\overline{X}$ is sample mean. N is sampling points.

Integral mean value of absolute value (IAV):

$$IAV = \frac{1}{N}\sum_{i=1}^{N} |X_i| \tag{3}$$

Root mean square:

$$RMS = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N} X_i^2} \tag{4}$$

Number of zero crossing (ZC):

$$ZC = \sum_{i=1}^{N} sgn(-X_i X_{i-1}) \tag{5}$$

Variance (VAR):

$$VAR = \frac{1}{N-1}\sum_{i=1}^{N} x_i^2 \tag{6}$$

It mainly consists of iEMG and RMS in time domain analysis respect. Calculation method of iEMG is:

$$iEMG = \int_{t}^{t+T} |EMG(t)|dt \tag{7}$$

Calculation method of RMS is:

$$RMS = \left(1/T\int_{t}^{t+T} EMG^{2}(t)\,dt\right)^{1/2} \tag{8}$$

Variation characteristics of sEMG signals amplitude can be reflected by iEMG and RMS in time dimension, whereas the latter depends on internal connection between muscular overloaded factors and physiological and biochemical process, therefore, the above indexes of time domain analysis are used to reflect active state of muscles real-timely without damage.

The main analysis method is to obtain frequency spectrum and power spectrum of sEMG by FFT of sEMG in frequency domain analysis respect. It can reflect change of sEMG in different frequency component, consequently it can reflect change of sEMG in frequency dimension. Mean Power Frequency (MPF) and Median Frequency (MF) are used for quantitative characterization of sEMG's frequency spectrum or power spectrum. The calculation methods are presented as follows:

$$MPF = \int_{0}^{\infty} fp(f)\,df \Big/ \int_{0}^{\infty} P(f)\,df \tag{9}$$

$$\int_{0}^{MF} P(f)\,df = \int_{MF}^{\infty} P(f)\,df = \frac{1}{2}\int_{0}^{\infty} P(f)\,df \tag{10}$$

where P(f) is EMG power spectrum. Because FFT spectrum curve of sEMG is not typical normal distribution, spectrum characteristic of sEMG characterized by MF is better than MPF from statistics perspective. But the sensitivity of MPF is better than MF's in specific work.

3 Tactile and slip sensing

The research of hand prostheses' tactile and slip sensing began in the 1960's, slip sensors are installed on the fingers of prosthetic hands to increase hand wrest strength when object slips. University of Southampton in England developed a prosthetic hand with thumb, forefinger and middle finger. The sensors installed on the latter two fingers are force sensing resister (FSR) sensor of Interlink. It can identify surface micro-vibration when object slips. FSR sensor has many applications in prosthetic hand sensing system. Andrea T et al.[15] also use these sensors and add sensing system to prosthetic hands of OTTO BOCK. FSR piezoelectric sensor is composed of two polymer thin sections. The thickness of thin sections is 0.2mm. One section consists of semiconductor materials, the other one is composed of mesh electrode. When the pressure is increased, the impedance of electrodes raises[16]. The contact of semiconductor materials and electrodes comprises a circuit to decrease the impedance. Mingrino [17] also utilizes Interlink corporation's sensors to design a slip sensing system for hand prostheses. When prosthetic hand grasps object, tilt table with metal disk and rubber transforms contact force to the sensor. Inline force and tangential force are obtained by sensor array with four same sensors.

In addition, there still have various methods of sensory feedback. Yamada et al. [18] use three dimensions force sensors to detect tactile and slip sensory. David et al. [19] utilize gas pressure sensor assembled in fingers of prosthetic hand to acquire pressure signal, and it feeds back to control system. Another approach is the study on the measurements of the force by strain gauge on prosthetic hand [20]. The connector is between thumb and other fingers. The relationship between the force on thumb and the stress on connector is approximately linear. In order to measure the force on thumb when object is grasped, strain gauges are pasted on connector to obtain the value of voltage by bridge circuitlink, amplification, and low-pass filter. Maeno et al. [21] make elastic fingers via silicone resin. And it is installed in artificial fingers to acquire tactile feedback. The goal of these examines is to improve feedback and bionic performance. There also have a host of studies regarding sensing technology in china [22], the work of EMG prosthetic hand with tactile and slip sensors is conducted in Tsinghua University [23].

Sensory feedback technology is also widely employed in robot hand. Dario et al. [24] assemble tactile sensors on robot hand[25]. Grasping force and displacement are controlled via tactile feedback and potentiometer on finger joints. Mingxin Jia et al. [26] utilize tactile sensors based on the principle of total internal reflection as feedback system. It is installed in multi-contact robot hand to achieve the interaction of operating arm and outside. Besides, distributed tactile sensors are used to provide feedback information and control grasping force [27].

Shimojo M et al. develop a new type of tactile sensor via pressure sensitive conductive rubber in Electro-Communications University. And the tactile sensors are installed in four fingers of robot hand to conduct the research of grasping cylinder and sphere. The result shows that the tactile sensor have advantages of flexibility, durability, and so on [28]. The sensor uses pressure conductive rubber as pressure sensitive materials. The rubber consists of non-uniformed distributed carbon particle, which is used as electrode. Without pressure, there is no contact between carbon particles, so the impedance is infinite; when pressure is added, thickness of carbon particles is thin, carbon particles become a contact chain, and the value of impedance gradually decreased.

Toshiham MUKAI [29] develops a soft large area tactile sensor which is applied to Symbiotic Robots, and its core component is semiconductor pressure sensor array. Symbiotic Robots with the sensors is used in patient care, human-computer interaction, and so on successfully. One of the main characteristics of the semiconductor pressure sensor array is its safety and dexterity of manipulation.

4 Proximity sensing

Unlike tactile and slip feedback, proximity sensing is mainly used to judge contact surface of prosthetic fingers and target object, external texture, shape feature, and so on. It includes the research of surface detection via method of image and memory alloy.

Angelo et al. [30] employ the technique based on stereo images and laser scanning, and use graphics system with higher performance price ratio to perceive surface shape, which avoids using expensive sensors and complex signal processing system. This proximity sensor has advantages of simple structure and low cost, and its circuit of microprocessor is 8 bit.

Wangtai L [31] detects contact surface by optical method, which is based on optical total reflection. The system is composed of tactile sensor and interface information display. The tactile sensor based on optical total reflection can provide high resolution and high quality tactile image. And it is installed in five fingers of manipulator to conduct experiment. The system consists of elastic film, transparent soft rubber light wave guide way, PMMA matrix, lens, optical fiber, and slim light source. The light source is located in specific tube to avoid divergent light. And it can be imported into light wave guide way. Normally air contacts the guide way, whereas refractive index of air is smaller than the guide way's. According to optical total reflection, the light in guide way won't refract, but when the fingers touch object, the guide way contacts the matrix. Because refractive index of matrix is small, the light in guide way will refract and be received by charge couple device (CCD), thus it can express surface features. Transmutable materials are used in this method, consequently the sensor have high resolution. It have 1600 contact points in every square centimeter, which can detect the force that is smaller than 2g. This sensor has advantages of high resolution, fast response, low cost, simple structure, and so on.

Because vision sensor can't solve the problem that mobile robot cannot avoid obstacle all-weather, Guanjiao Ren et al. [32] design position sensitive detector (PSD) as detecting element of vibrissa bottom. And each bottom of vibrissa is installed laser proximity sensor to determine the displacement of obstacle. Boby George et al. use inductance-capacitance proximity sensor to detect occupation of vehicle seat. It can shield environmental electric field effectively and distinguish the difference between individual and object in occupation of seat [33]. In the premise that the number of location target is limit and the precision and effectiveness of location is not high, Xiaolong Xu et al. develop a new type of proximity sensor [34]. Sean Walker et al. design an optical fiber proximity sensor for tactile detection of robot fingers [35]. This sensor detects intensity of laser in surrounding two-dimensional section by emitting infrared light to obtain surrounding environment information. It achieves much better result in tactile detection, pre-contact velocity reduction control, and non-contact contour based on surface curvature.

Heng-Tze Cheng et al. [36] develop a new type of contactless gesture recognition system based on proximity sensor. It adopts unique infrared signal feature extraction. Three dimensional hand motion is recognized and classified by binary decision tree in real time with an accuracy of 98 percent. This system overcomes the shortcoming of high computational complexity and high power consumption. The system has advantages of low power consumption, high recognition accuracy and high flexibility. And it has a good application foreground in mobile terminals and contactless game machine. There is a development flow of contactless mobile terminal, as shown in Fig. 3.

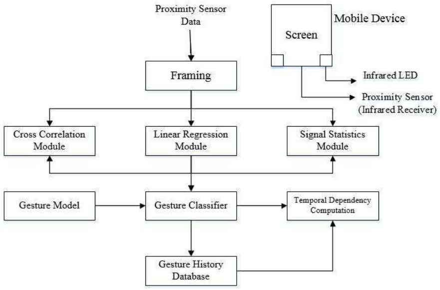

Figure 3. Gesture recognition system diagram of mobile terminal based on proximity sensor

5 Cold and hot sensing

In addition to tactile and slip sensing, cold and hot sensing also is quite important for hand prostheses. Cold and hot sensory is one of the fundamental sensory. It will hurt human hand if the temperature is too low or too high. Meanwhile it will destroy the surface materials of prosthetic hand. Thus cold and hot sensory feedback is an integral part of prosthetic hand's research. Currently, the Peltier materials are applied to most thermal sensing feedback. The feedback system studied by Ino is composed of Peltier module and proportional integration differential (PID) [37]-[39]. It is mainly used for the identification of objects contacted by the fingers and the

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identification of objects' surface by perceiving its change of temperature. The identification of thermal sensory is made by changing the temperature of aluminum, glass, rubber, polymer, timber, and so on. The experiment shows that recognition rate of aluminum and timber is 91% and 82%, respectively; recognition rate of glass, rubber, and polymer is between 40% and 50%.

Leoni et al. [40] develop an integrated sensor. Its thermal sensor consists of two micro resistance that is embedded in heat conduction rubber. One of the micro resistances is used for heating, another is used for the detection of temperature's change, accordingly, the sensor needs heating and measure phase. When it is in energized state, the temperature of sensor is heated to a certain value by thermal resistance. When thermal resistance has no electricity, temperature change relative to time is detected. And this function is related to the heat conduction between the sensor and object.

Seung-II Yoon and Yong-Jun Kim [41] embed thermoelectric materials and thermopile in high molecule polymerization films, which can detect contact temperature and contact pressure. By Seebeck effect, the temperature of the sensor's surface and its internal temperature are transformed into electrical signal for accurate detection. When force is added to the sensor, deformation of the sensor will change the resistance of thermopile. And applied force can be detected by the resistance.

Y.-J.Yang et al. [42] design an 88 sensitive array with tactile and thermal sensory in flexible polyimide copper film by micromachining technology in National Taiwan University. The copper film is composed of positive and negative sensitive unit array. The positive surface is semiconductor temperature sensor, and the negative surface is conducting polymer tactile sensor. Its special manufacturing method eliminates current coupling crosstalk of each sensing unit. And there is no degradation in sensing function when its radius bends to 4 mm.

The research of thermal attributes sensor done by Jianfeng Wu et al. [43] shows that the adopted temperature tactile method can distinguish different thermal attribute objects. Lyneae AJones and Michal Berris [44] develop a sensor that can distinguish thermal attribute by temperature and its change. Five different thermal attribute objects are picked and distinguished by two ways. One of ways depends on temperature, the other counts on heat conductivity. The result shows that different thermal attribute objects can be distinguished only when temperature change gradient is high. When hand touches surface of copper, brass, nickel, stainless steel, or nylon, only nylon can be distinguished. Because thermal conductivity of nylon is smaller than other materials.

6 Multi-sensing fusion

On the basis of various sensory feedback, multi-sensing fusion is developed. Various sensory feedback sensors are installed on prosthetic hand to receive sensing signals and feed back to control system.

Dario et al. [45] develop a multi-sensor system which can detect various information including proximity sensing, joint torque, tactile sensing, and so on. Tree different materials are used in this multi-sensing fusion, namely, strain gauge, semiconductor polymer, and piezoelectric polymer[46]. The bottom is force torque sensor, and the applied tactile array is 256 array which is based on FSR. The upper layer is a sensor used to detect dynamic sensory. And it needs the support of piezoelectric polymer materials. Another part is ultrasonic sensor, which can emit and receive ultrasonic, and can detect geometry of target object within a certain range. After receiving signals of multi-sensor, control system processes signals and issue instructions. Dario et al. develop another type of multi-sensor, and its dynamic sensor is composed of polyvinylidene fluride (PVDF). Gripped object slips, which causes vibration of PVDF, so slip sensory can be detected. FSR sensor is used as switch sensor, and threshold of contact force is set to judge whether object are gripped.

The multi-sensor developed by Taddeucci et al. [47] is composed of tactile, thermal, and dynamic sensors. It can be used to detect contact images, measure heat conductivity and micro-vibration in slip sensing. Aligned array sensor is used in tactile sensing, which can detect contact situation in each unit area. Dynamic sensor consists of piezoelectric crystal elements. The elements with the Peltier effect are used in thermal sensor.

Darwin develops a multi-sensor, which can detect hardness, surface characteristics, temperature, slip, surface profile, and heat conductivity [48]. It is composed of polymer fiber, electromagnetic field system, thermocouple, elements with the Peltier effect. Among which: 1 plastic fiber array (infrared diode source, plastic fiber, infrared sensitometer) based on principle of total reflection is used in stress, hardness, and shape sensors. 2 measurement of temperature is acquired by a simple thermocouple, data of heat conduction is produced by the Peltier effect. Peltier device acquires change of temperature and outputs voltage which can be measured quickly and accurately. This Peltier strain gauge is pasted in tip of finger. 3 high sensitive device with electromagnetic field is used in texture and sliding. Vibration between fingers and object is transported by sensing probe tied on rubber membrane. When object slips on the surface of fingers, movement of probe drives armature movement and changes magnetic field to acquire sliding induction. The result shows that identification accuracy of texture is above 90%, resolution of iron and aluminum has reached 90% in thermal sensory feedback experiment, and foam has reached 84%.

Multi-sensing fusion can detect various signals, which is very benefit for grasping object in control system [49]. But it is complicated in structure installation, there is other receiving system, and algorithm and velocity of control system need to be considered [50]. This complex feedback system can be applied to robot hands with high requirement. It is favorable if the system can be applied to intelligent prosthetic hand, but it needs further study for hand prostheses. The best way is to find a kind of material which can detect various sensory, or neglect unimportant sensory, and focus on the base sensory.

7 Research prospects

The research of sEMG hand prostheses has significant social benefits and is quite a challenging work. But there still have some further research. The research mainly focuses on the following aspects:

(1) The detection of thermal conductivity sensory needs stable heating source in long time. The requirement of power reserves and stability is high, which can only be met by applying power source at present. The research of micro thermal conductivity sensor with array layout of multiple points can reduce power cost and improve velocity and precision of measure, which is a direction.

(2) The output response signal of PVDF hardness-softness sensor has relations with contact position, contact area, and contact force. The deep analysis of mechanical structure and the way of loading contact force is required to get more accurate hardness-softness information.

(3) Compared with human hands which is multifunctional and dexterous, the research of sEMG hand prostheses is still preliminary. While progress has been made, there is a long way to go.

8 Conclusion

The theory of sEMG and its signal analysis technology are introduced and sEMG sensing techniques for hand prostheses are surveyed in this paper. These sensing techniques include tactile and slip sensing, object's surface characteristic sensing, cold and hot sensing and multi-sensing fusion. Tactile sensing is used to judge the contact of robot hand and object or measure the characteristics of object. Slip sensing is used for the judgment and measure of object's slippage. It is actually a sensor system for displacement measurement. Proximity sensing is mainly used to judge the surface situation of hand prostheses and aim object, texture and shape characteristics including surface shape detection research of image method and memory alloy method. Cold and hot sensing is an integral part of hand prostheses research. Currently, Peltier materials are used in most thermal feedback system. The research of hand prostheses with multi-sensory, multi-degree-of-freedom, high integration, and miniaturization is a trend. Not only the research and efforts of this field has great theoretical value, but also has great market value. In the end, several challenges and directions are concluded.

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