Research and Design of Electrical Stimulation Electrode Arrays Device

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Abstract. A wireless electrical stimulation device based on biological electrode array is developed. The stimulator uses the FPGA as the central controller, a 4×4 electrode array is built and direct digital synthesizer (DDS) is used to generate stimulating waveforms. To generate adequate current load on human body, an isolated bi-direction constant current source module is designed which can detect electrode loss, as well as provide safe bi-direction constant current. The host computer uses an interactive software for android system, and the stimulating amplitude, pulse width and frequency and the electrode selection can be adjusted flexibly. The ES electrode arrays device has the characteristics of small size, good stability, low power consumption, easy to operate. It will bring convenience to clinical applications and bioelectrical stimulation scientific researches.

Key words: electrode array, bioelectrical stimulation, FPGA

1. Introduction

Electrical stimulation (ES) has been widely used in the fields of clinical rehabilitation, neuro-electrophysiology and bioinformatics. ES uses electric impulses to artificially activate related motor neurons making muscle contraction [1]. ES is supported by a growing body of clinical evidence[2], and has become an area of intense engineering and clinical research over the last few years[3, 4]. Compared with single pad ES electrode electrical stimulation (ES) applying electrode arrays is an emerging bioelectrical stimulation technology. It has the potential to improve selectivity, automate placement, and reduce fatigue and discomfort[5, 6]. Moreover, the size and shape of the electrodes can be adjusted according to users that means they can stimulate smaller muscle groups and enable the user to perform specific motions[7, 8].

A major aim of ES electrode arrays research is to provide a portable, safe and user-friendly device that patients can use at home to support independent living. This paper analyzes the technical essentials and
flaws of ES electrode arrays device, and provides corresponding solutions. A low power consumption, an electrical stimulator using electrode arrays was developed.

2. Stimulator System Design

2.1. Design Requirement
In order to develop a comprehensive, safe, stable and user-friendly stimulator, the following 5 requirements described should be satisfied.

(1) To provide multiple stimulation modes, the stimulator should be able to generate stimulating currents in different amplitude, frequency, waveform, and polarity. Generally, the impedance of human body between electrodes is about 1k to 3kΩ, if the simulating current is 20mA, a 20~60V power supply is needed. In the existing constant current stimulator, to ensure a sufficient current loading into human body, high voltage is usually around 80 V [9]..

(2) To perform various stimulus modes, such as intermediate frequency therapy, the stimulating frequency need to be above 1kHz, so the controller is required to select one or a group of electrodes quickly.

(3) The array electrodes stimulator have many stimulation sites, each stimulation site should be able to independently selected, and the switching consuming time should be as less as possible, and stimulating sites can be switched quickly to ensure the demand for intermediate frequency electrical stimulation.

(4) To ensure the safety and stability of the stimulator, it is necessary to isolate the power supply and signal.

(5) Array electrodes require adequate control lines, so wearable design is adopted to facilitate users.

2.2. Stimulator Design Model
As shown in Fig.1, the electrical stimulator consists of two parts: the wireless stimulating actuator and the host controller. To facilitate users, the wireless stimulating actuator is designed to be wearable, and the host controller controls the stimulator actuator through Bluetooth.

![Fig.1 System Diagram of ES Electrode Array Device](image)

The stimulating actuator employs an FPGA as the central controller, which has the advantages of low power consumption and high performance. A 4x4 electrode array module is built and direct digital synthesizer (DDS) is used to generate stimulating waveforms. To ensure the adequate current load on human body, an isolated bi-direction constant current source module is designed to detect electrode loss, and provide safe bi-direction constant current.

2.3. Electrode Array Module
As shown in Fig. 2, a 4×4 electrode array is built.

U1~U4 and U9~U14: switches connect the electrodes and the A point. U7~U1 and U19~U22: switches connect the electrodes and the B point. ELC: electrode

Every electrode connects to two random-phase triac driver output opto-couplers which enable current flowing in two directions. These opto-couplers connect to nodes A and B which lead to the constant flow source. By turning the opto-couplers on and off, any set of electrodes can be chosen, for example: U1, U19 switches are on, the other switches are off, the current would flow through A→U1→ELC1→human body→ELC5→U19.

To further improve the switching speed, parallel multiplexing method is employed here, and a maxim latching speed of 15ns is achieved. Moreover, the speed will not be constrained by the number of electrodes conducted.

2.4. **Isolated Bipolar Constant Current Source Module**
The isolated bipolar constant-current source module is demonstrated in Fig. 3. This module includes an isolated H-bridge commutator circuit, a voltage-controlled constant current circuit and an electrode drop detection circuit. The advantage of the circuit is steady constant-current and high isolation and withstand voltage [10].

The H-bridge commutator circuit (R1–R4, U1–U4, Electrode Array) is designed to support the bi-direction stimulating current. In order to ensure user’s safety, this circuit is isolated by four opto-isolators (PC817) with an isolation voltage up to 5000V.

The voltage-controlled constant current circuit is composed of a linear opto-coupler (HCNR201), a rail-to-rail amplifier, and symmetrical triodes (Q1 and Q2) circuit which is used for enlarge current.

To insure reliable contact between electrodes and the skin, electrode loss detection circuit is designed. This circuit detects the stimulus waveform, using a High Speed Logic Gate Output Opto-coupler 6N137 being in series with the H-bridge commutator circuit. The detection current of 6N137 can be as low as 300μA to 50mA, with a detection speed up to 10MBd, meeting the requirements of various bioelectrical stimulation. If the output pulse width from a stimulation is 25μs, a 25μs pulse can be detected in the detection side of 6N137. In order to exclude the failure of pulse detection caused by the photo-couplers’ damage, before stimulating the FPGA outputs two test pulses, the U1 and U3, U2 and U4 connect to the circuit separately, so that the test pluses can bypass the electrode and flows to the electrode loss detection circuit (6N137). If pulses can be detected that indicates the photo-couplers U1-U4 are not damaged, if not, the photo-couplers could be damaged.

2.5. Waveforms Generating Module
As shown in Fig.4 a Direct Digital Synthesizer (DDS) is been used for generating stimulating waveforms. DDS has been widely used biomedical equipment applications for its advantages as agile sources of low-phase-noise variable-frequencies with good spurious performance, and simply generating a frequency stimulus, etc [11, 12].

![Electrode Drop Detection Circuit Diagram](image)
The host computer sends the waveform data to FPGA, the data firstly stores in a FLASH chip W25Q64. When the waveform output command is received, FPGA takes the data out from the FLASH chip in accordance with the frequency data given by host computer, and feeds it into the D/A converter (AD9703). After passing through a low-pass filter, the corresponding stimulus waveform can be obtained. Waveform amplitude is adjusted by a digital potentiometer TPL0501, it is a single channel linear digital potentiometer, with 256 cursor position and a 100 kΩ end-to-end resistance. The FPGA adjusts the amplitude of waveform by setting the location registers of TPL0501.

3. Software Design
In order to make the device more convenient and user-friendly, the host controller adopts Android system, which can be applied in a mobile phone or a tablet. The development environment of the host controller system is Eclipse 6.0, and the programming language is JAVA. Software functions include Bluetooth communication, stimulus current parameters setting and waveform display, electrodes mode and scheme setting, current loading and etc.

The major function of the wireless stimulator actuator is to set stimulus parameters and executive commands from the host controller. The modular design is used in the actuator for its readable, good portability and meanwhile easy to upgrade for different stimulating needs. The wireless stimulator software includes parallel port communication module, waveform output module, amplitude control module, electrodes selecting module, a current polarity switching module, pulse width and frequency setting module, constant current source module and power management module.

4. Results
Using a 1 kΩ resistance as load, we tested the stimulator’s working frequency, pulse width, ripple and power consumption (static and full speed), the results are shown in Tab.1. A 3.7V, 1500mAh polymer lithium battery power is adopted as power supply, it can support full speed continuous stimulating for about 3 hours.

| Output current (mA) | Frequency (Hz) | Pulse Width (%) | Ripple Voltage (mV) | Power Consumption (mW) |
|---------------------|----------------|-----------------|---------------------|------------------------|
|                     |                |                 |                     | Static     | Full speed$^1$ |
| 10                  | 0~2000         | 1~100           | <20                 | 47.2       | 468.3         |
| 30                  | 0~2000         | 1~100           | <40                 | 47.5       | 1310.7        |
| 0~30$^2$            | 0~2000         | 1~100           | <22                 | 47.3       | 512.6         |

Tab.1 Output parameters of different stimulation current
Note: 1) At full speed, output rectangular wave, pulse width 50%, frequency 2000Hz, 16 electrodes are all selected; 2) During intermittent stimulation, the output current varies randomly between 0 and 30mA.

5. Conclusion
An ES electrode array device is designed and developed which includes a host controller system and a potable wireless stimulator. The stimulation parameters of the ES electrode array device is showed in Tab.2.

| Stimulation parameters       | Range (Resolution)                                      |
|------------------------------|--------------------------------------------------------|
| Number of isolated channels  | 16                                                     |
| Output characteristics       | Constant Current                                       |
| Waveform                     | Biphasic, asymmetric, charge-balanced, arbitrary waveform |
| Current output               | 0~35mA                                                 |
| Pulse amplitude              | 80V max per channel (load dependent)                   |
| Pulse frequency              | 1~2000Hz                                               |
| Pulse duration               | 0.02 ~1ms                                              |
| Pulse phase                  | 0~180°                                                 |

Tab.2 The stimulation parameters of the ES Electrode Arrays Device

An ES electrode Array device is developed in this article. It has the following characteristics: stimulating parameters can be adjusted flexibly, plenty of stimulation functions can be provided and expanded easily, low power consumption, small size and wireless design, friendly operating interface, good interactivity and safety. Experimental results indicate that the stimulator works stably and can meet the requirements of bioelectrical stimulation both in clinical and research.

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