Improvement of Implantable FES System with Fail-Safe Circuit

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Abstract

To improve safety of the implantable FES system in its operation, the error detecting and correcting circuit was applied to it as one of its fail-safe methods. The circuit is based on the Hamming SEC-DED (a single-bit error correcting and double-bit error detecting) coding, makes high-speed error detection and correction feasible, and allows hardware simplicity. In this paper, the selection data of the stimulus pulse were encoded and decoded. For miniaturization of the circuit, a field programmable gate array (FPGA) was used. The digital circuits of the transmitter and stimulator were designed, the simulation of circuits was performed using FPGA design tool, and the outputs of the FPGA device were observed using oscilloscope after downloaded the circuit data to the EEPROM. From the simulation and experimental results, it was clear that the designed circuits were effective for the implantable FES system.

Keywords: implantable FES system, error detecting and correcting circuit, fail-safe, FPGA

1. INTRODUCTION

To restore rationally and effectively motor functions of paralyzed extremities in spinal cord injury patients, the functional electrical stimulation, FES, is attracted the attention of people all over the world. Electrodes, such as percutaneous intramuscular electrodes [1], [2], and surface electrodes [3], are utilized in the present FES system. For the selective activation of individual muscles, the former ones are suitable. Because of the percutaneous intramuscular electrodes penetrating skins, the system using these electrodes has some unavoidable problems. For example, daily maintenance before and after taking a bath is quite a burden on users and their families, the regions where electrodes go through skin are not cosmetically favorable and infection could occur.

Totally implantable FES systems have been developed recently. By means of using the electromagnetic induction, implanted stimulators are externally controlled. Their driving powers and stimulus data are transmitted from transmitters to receivers of the stimulators using inductive coils. Most of them, however, have any possibilities that errors in transmitted stimulus data occur due to electromagnetic noise. This may disturb to restore the motor functions. In the worse cases, that causes standing patients to fall to the ground. It is crucially important to consider that they should be prevented from being injured by falling to the ground with the aid of fail-safe techniques.

In general, error correcting codes are employed to correct received erroneous data. This paper describes design of the implantable FES system with FPGA (field programmable gate array) and applying high-speed encoder and decoder using the Hamming coding to it.

2. METHODS

2.1 System configuration

A configuration of the implantable FES system [4]-[6] is shown in Fig. 1. The external unit is placed outside of the body and the stimulator is implanted inside the body. They have electromagnetically coupled coils. Power and stimulus data are transmitted from the external unit to the stimulator by means of the electromagnetic induction. Some data with respect to the stimulator, such as a shortage of the power supply or a displacement of the coils, are returned from the stimulator to the external unit. Therefore, this system does not require any percutaneous intramuscular electrodes because of both the stimulator and overall electrodes being implanted.
2.2 Error detecting and correcting circuit

As one of the fail-safe techniques, there is a method to use the error correcting codes for transmission of information. In numerous codings, the Hamming SEC-DED (single-bit-error correcting and double-bit-error detecting) coding is very useful. Although multiple-bit errors are not correctable with the SEC-DED codes, it has two advantageous features: (1) high-speed encoding and decoding circuits and (2) simple circuit structures. The smaller for a decoder incorporated into the implanted stimulator, the better. As far as the transmission of information is concerned, it is also desirable that encoding and decoding delays are as small as possible. Thus, the encoder and decoder based on the Hamming SEC-DED coding were applied to our implantable FES system. The H matrix for the coding is given by the following equation [7].

\[
H = \begin{bmatrix}
    1 & 1 & 1 & 0 & 1 & 0 & 0 & 0 \\
    1 & 1 & 0 & 1 & 0 & 1 & 0 & 0 \\
    1 & 0 & 1 & 1 & 0 & 0 & 1 & 0 \\
    0 & 1 & 1 & 1 & 0 & 0 & 0 & 1 \\
\end{bmatrix}
\]

2.3 Simulation and Experiment

A block diagram of the stimulator of the implantable FES system is shown in Fig. 2. The circuit was designed using FPGA design tool, Quartus II (ver.5 Web ed., ALTERA Co., Ltd.).

The transmission data are composed of 24 bits. They are start bit of 1 bit, mode selection of 2 bits, channel number of 4 bits, amplitude data of 12 bits, check bits of 4 bits, and stop bit of 1 bit, respectively. In this paper, the channel selection data were encoded and decoded using Hamming SEC-DED coding.

The digital circuits of the transmitter and the stimulator were designed, and the circuit simulation was performed using Quartus II. Then, the data were downloaded in a FPGA device, FLEX EPF10K10LC84-4, with EEPROM, EPC2LC20, and outputs of the FPGA device were observed with an oscilloscope.

3. RESULTS

An example of simulation result of the digital circuits is shown in Fig. 3. It was clear from the simulation result that the designed digital circuits of both the transmitter and stimulator performed appropriately, and that the decoder could output corrected channel data when the 1-bit erroneous channel data were transmitted from the transmitter.
The experiment result is shown in Fig. 4. “ECC out” stands for the output signal of the error detecting and correcting circuit. When the circuit outputs “high” level as shown in Fig. 4, this means that more than 2-bit errors do not occur. If this outputs “low” level, more than 2-bit errors occurs. In this case, the stimulator stops to output any stimulus pulses immediately.

**4. DISCUSSION AND CONCLUSIONS**

Stimulus data of the stimulator have two significant stimulus parameters such as the channel selection and stimulus amplitude. When 1-bit error occurs on the latter data, a muscle is stimulated by improper amplitude of stimulus pulse. That could be over or under amplitude than the proper one. Only the muscle is influenced in this case. On the other hand, two muscles are influenced when 1-bit error on the former data occurs. In other word, one muscle is not stimulated at this time, and the other muscle is stimulated by improper amplitude of stimulus pulse. Therefore, the channel selection data are more significant than the stimulus amplitude data. To handle the Hamming SEC-DED coding efficiently, the former data should be encoded.

It was obvious from both simulation and experimental results that the digital circuits of the transmitter and stimulator were designed appropriately. A further consideration of integration of digital and analog circuits for the implantable FES system should be needed for our future work.

**References**


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