35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

A Microprocessor-based Multichannel Subsensory Stochastic Resonance Electrical Stimulator

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Abstract—**Stochastic resonance electrical stimulation is a novel intervention which provides potential benefits for improving postural control ability in the elderly, those with diabetic neuropathy, and stroke patients. In this paper, a microprocessor-based subsensory white noise electrical stimulator for the applications of stochastic resonance stimulation is developed. The proposed stimulator provides four independent programmable stimulation channels with constant-current output, possesses linear voltage-to-current relationship, and has two types of stimulation modes, pulse amplitude and width modulation.**

I. INTRODUCTION

Stochastic resonance (SR) stimulation utilizes random subsensory electrical noise into the nervous system to enhance the detection of weak sensorimotor signals [1-9]. Stochastic resonance stimulation therapy has been useful for improving in somatosensory sensitivity [1-3], muscle spindle receptor response [4], posture control [5-8], and joint proprioception sensation [9]. To enable the investigation of a variety of SR applications, a versatile multichannel white noise electrical stimulator is required. Therefore, the purpose of this study is to develop a microprocessor-based multichannel subsensory white noise electrical stimulator for various SR applications. In the proposed SR electrical stimulator, a stimulation pulse pattern generation method is proposed to produce pulse amplitude and width modulation patterns. A voltage controlled constant current circuit is designed to provide a linear current output. A PC-based graphic user interface (GUI) program is also implemented to transmit the white noise patterns to the NAND flash of the proposed SR electrical stimulator via RS232 interface.

II. SYSTEM DESIGN

The multichannel subsensory SR electrical stimulator consists of a Samsung S3C2440 core board, a TFT LCD touch screen panel, an AD5324 quad 12-bit digital to analog converter (DAC), and a voltage controlled constant current circuit. The block diagram of multichannel subsensory SR electrical stimulator is shown in Fig. 1. The S3C2440 core board is responsible for receiving the commands from the TFT LCD touch panel controlled by operator and generating the stimulation pulse waveform according to the received commands to the stimulation electrodes through voltage controlled constant current circuit. The zero mean Gaussian white noise is generated using Matlab's toolbox and downloaded to the NAND flash of S3C2440 core board via RS232 interface.

*Resrach supported by the National Science Council (NSC 98-2221-E-214-020) ,Taiwan, ROC.

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A. S3C2440 core board

This S3C2440 core board is based on the 32-bit ARM920T core which operates at 400 MHz. The core board has 64MB SDRAM (HY57V561620) and 64MB NAND flash (K9F1208) and integrates a wide range of peripherals like JTAG interface, universal asynchronous receiver and transmitter (UART) interface, general purpose input/output ports, five 16-bit pulse width modulation (PWM) timers, LCD controller, serial peripheral interface (SPI), analog to digital converter (ADC) and touch screen interface, etc.

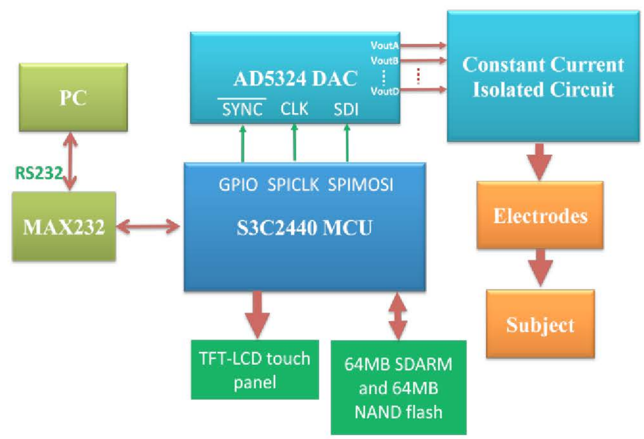

Fig. 1 Block diagram of multichannel subsensory SR electrical stimulator.

B. Stimulation Pulse Waveform Generation

Two PWM timers (timer 0 and timer 1) of S3C2440 processor is used to generate stimulation pulse waveform, as shown in Fig. 2. Pulse repetition frequency (the reciprocal of inter-pulse interval) is controlled by the timer 0. The timer 1 is utilized to control pulse width. The frequency and duty cycle of timer0 and timer1 is determined by configuring MPLL control (MPLLCON) register, clock divider control (CLKDIVN) register, timer configuration register0 (TCFG0), timer configuration register1 (TCFG1), timer control (TCON) register, count buffer register of timer 0 and timer 1 (TCNTB0/ TCNTB1).

With MPLLCON=0x7f021, CLKDIVN=0x05, TCFG0 =0x7C, and TCFG1=0x11, the frequency of input clock source of the timer 0 and timer 1 is programmed as 100 KHz. The output frequency of timer 0 (TOUT0) is controlled by configuring TCNTB0. The value of TCNTB0 is loaded into the down-counter when the timer 0 is enabled by setting the

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start bit of timer 0. When the down counter of timer 0 reaches zero, the interrupt request of timer 0 is invoked to notify the ARM920T core that the timer 0 operation has been completed. In the interrupt service routine 0, the timer 1 is enabled by setting the start bit of timer 1 and the value of TCNTB1 and pulse amplitude is given depending to the stimulation mode. The value of TCNTB1 is used to control the pulse width of stimulation waveform. If stimulation mode is pulse amplitude modulation (PAM), the value of pulse width is set to a fixed value and the value of pulse amplitude is given according to the value of white noise in the NAND flash and output to AD5324 via SPI interface. If the stimulation mode is pulse width modulation, the value of pulse amplitude is set to fixed value and the value of pulse width is modulated according to the value of white noise. After timer 1 is enabled, the value of TCNTB1 is loaded into the down-counter of timer 1. When the down counter of timer 1 reaches zero, the interrupt request of timer 1 is triggered. In interrupt service routine 1, the timer 1 is disabled and the pulse amplitude of stimulation waveform is set to zero. The flow chart of stimulation pulse waveform generation is shown in Fig. 3. The PAM white noise stimulation pattern and PWM white noise stimulation pattern is respectively shown in Fig. 4 and 5.

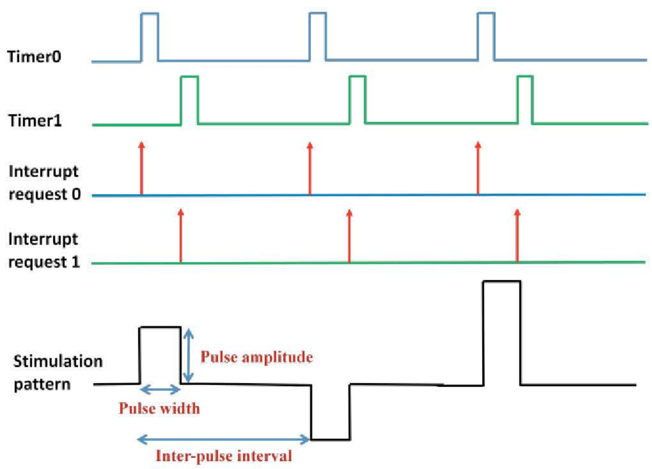

Fig. 2 Stimulation patterns generated by two timers of S3C2440.

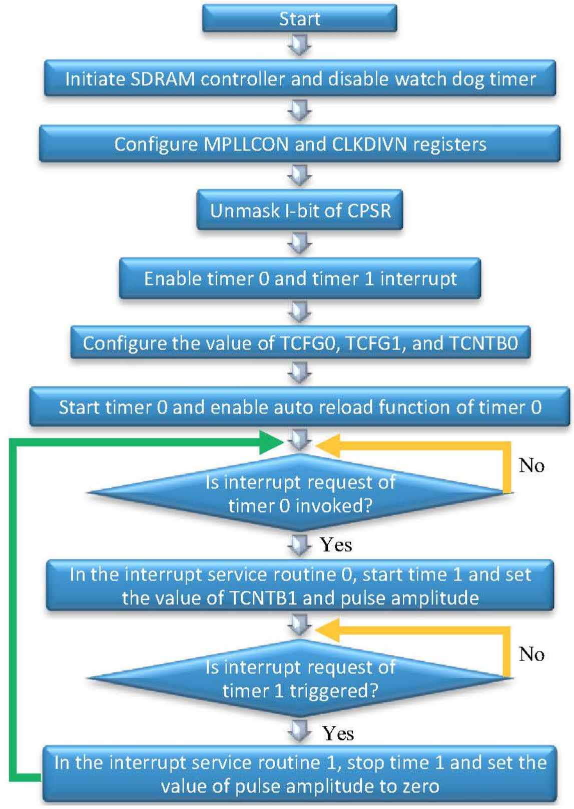

Fig. 3 The flow chart of stimulation pulse waveform generation.

C. Voltage Controlled Constant Current Circuit

The voltage controlled constant current source consists of an AD5324 DAC, a bipolar voltage source circuit, and a Howland current pump circuit. The schematic of the voltage controlled constant current source is shown in Fig. 6. The bipolar voltage source circuit is realized by using an operational amplifier (AD8512), two resistors, and a fixed input reference voltage. The output voltage (V1) of the bipolar voltage source circuit can be represented as follows:

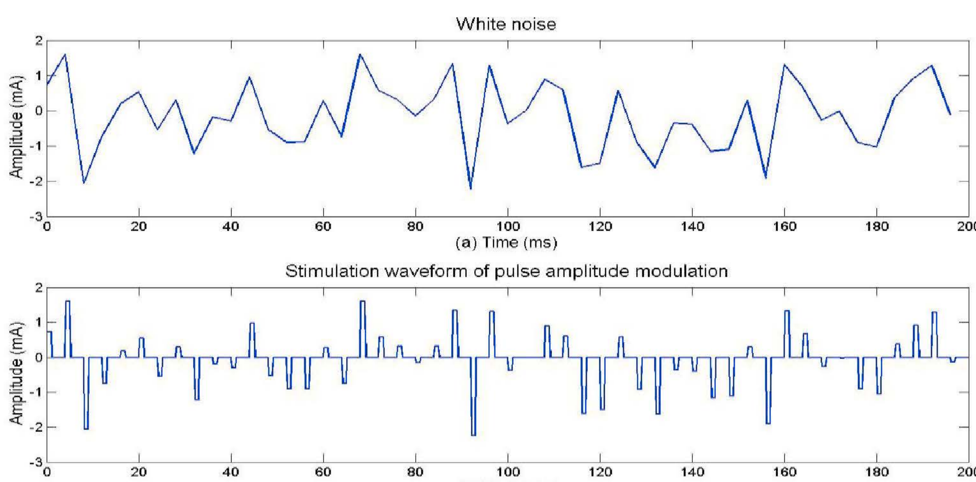

Fig. 4 (a) Zero-mean white noise, (b) Stimulation waveform generated by pulse amplitude modulation

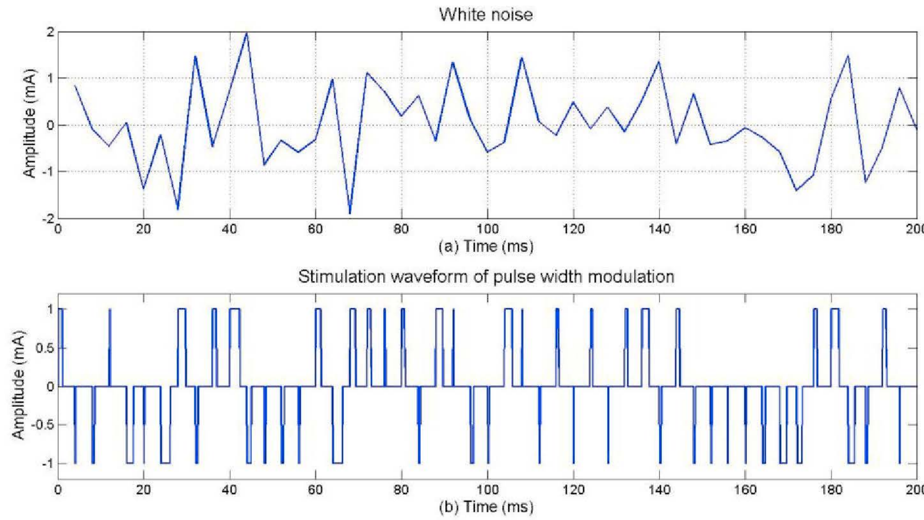

Fig. 5 (a) Zero-mean white noise, (b) Stimulation waveform generated by pulse width modulation

$$V_1 = \left[V_{DD} \times \frac{D}{2^{12}} \times \left(\frac{R_1 + R_2}{R_1}\right) - V_{DD} \times \frac{R_2}{R_1}\right]$$

where D represents the input code in decimal (0 to 4096). With V_{DD} = 5 V, $R_1 = R_2$ = 10 kΩ,

$$V_1 = \frac{10 \times D}{2^{12}} - 5V$$

This is an output voltage range of ±5 V, with 0x0000 corresponding to a −5 V output, and 0xFFF corresponding to a +5 V output.

Howland current pump is a voltage controlled current source with load impedance (Z_{LOAD}). The load impedance simulates the human tissue, which typically ranges from 500 to 2000 Ω [10]. Howland current pump has two advantages: high output impedance and bipolar output currents. Generally, to enhance stability, the circuit is symmetrical. Therefore $R_3 = R_3'$, $R_4 = R_4'$, and $R_5 = R_5'$. The output current (I_{LOAD}) through the load impedance (Z_{LOAD}) is almost independent of the absolute impedance of the load and only depends on the amplitude of the input voltage (V_1). The output current (I_{LOAD}) can be represented as follows:

$$I_{LOAD} = \frac{-(R_4 + R_5)}{R_3 \times R_5} \times V_1$$

With R_3 = 300 k Ω , R_4 = 18 k Ω , R_5 = 100 Ω , and V_1 is in between -5 V and 5 V, I_{LOAD} is programmable from -3 mA to 3 mA with a resolution of 1.465 μA (1 LSB at 12 bits), and the circuit has a very high output impedance.

D. Graphic User Interface

A PC-based graphic user interface program is developed by using Visual C++ 2010. In this GUI program, the operator can select available serial ports and baud rates from drop down list, and press the "Initiate Serial Port" button to initiate the selected serial port. If the response status of serial port is correct, the operator then can open the file of white noise data by pushing the "Open File" button and press "Send" button to transmit the white noise data to the NAND flash of S3C2440 core board via selected serial port interface.

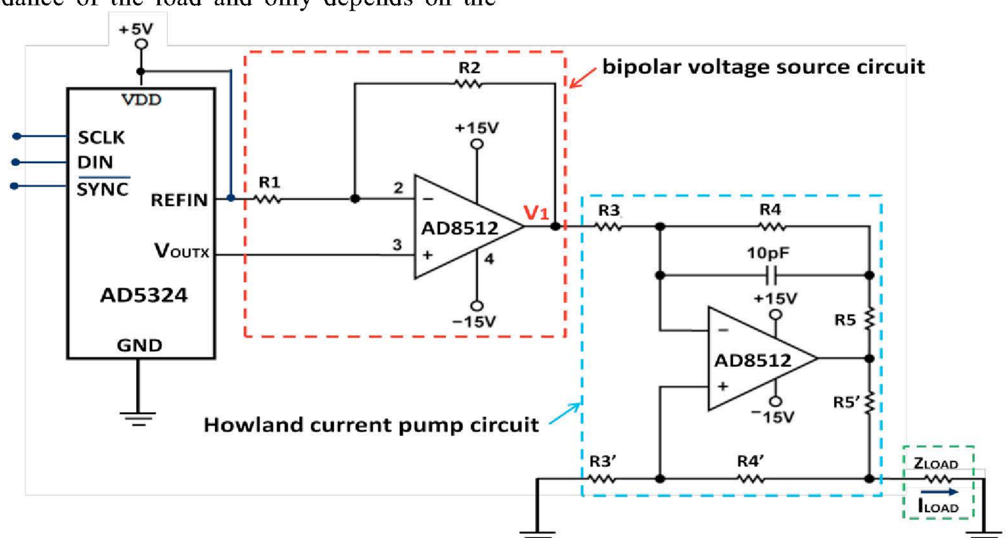

Fig. 6 Voltage controlled constant current circuit for a single channel

If the transmission is right, the "Transmission Complete!" message will be appeared.

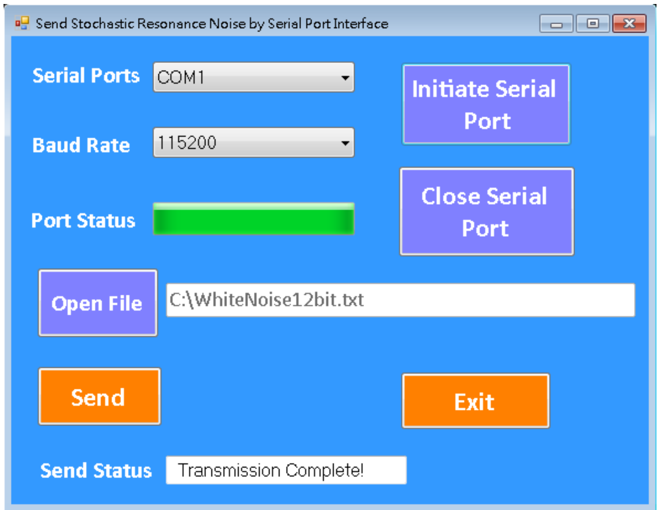

Fig. 7 A scenario of PC-based graphic user interface program for sending stochastic resonance white noise data via RS232 interface.

III. RESULTS

The system specifications of the proposed multichannel stochastic resonance electrical stimulator are summarized in Table I. The variation of the output current with respect to the output from the AD5324 digital-to-analog converter, which varies between -5 V and +5 V, is found to be linear voltage-to-current relationship as illustrated in Fig. 8. The stability to human tissue variation was measured by the load impedances ranging from 500 Ω to 5 KΩ. Fig. 9 shows the linear relationship between voltage and resistance at a current of 3 mA, offering a useable load impedance range from zero to 4.5 kΩ.

IV. CONCLUSION

A microprocessor-based multichannel subsensory white noise electrical stimulator was successful developed. The stimulator is suitable for the investigation of a variety of SR applications. The proposed system provides four independent programmable stimulation channels, possesses linear voltage-to -current relationship, and has two kinds of stimulation modes, pulse amplitude and width modulation.

Table I
System specifications of proposed stochastic resonance electrical stimulator

Number of Channels	4
Output mode	Constant current
Current output	±3 mA with 1.465 μA resolution
Max. voltage limitation	±15 V
Pulse frequency range	10 ~ 500 Hz
Pulse width range	50 ~ 2000 μs
Time resolution	10 μs
Interface with host PC	Serial port, 115200 bps
Software platform	Windows 7

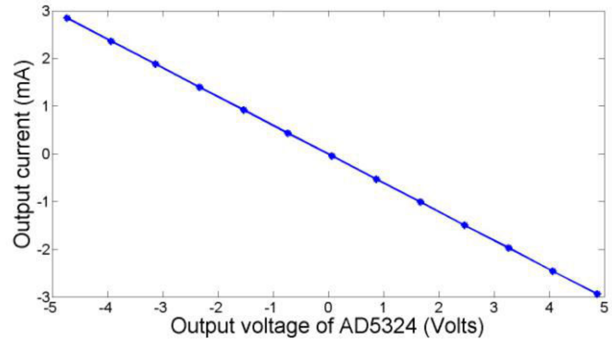

Fig. 8 Voltage-to-current relationship.

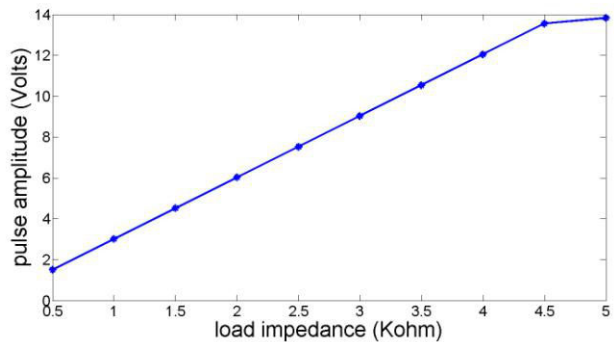

Fig. 9 Constant current relationship of output

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