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A Wideband Wireless Neural Stimulation Platform for High-Density Microelectrode Arrays

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Abstract—**We describe a system that allows researchers to control an implantable neural microstimulator from a PC via a USB 2.0 interface and a novel dual-carrier wireless link, which provides separate data and power transmission. Our wireless stimulator, Interestim-2B (IS-2B), is a modular device capable of generating controlled-current stimulation pulse trains across 32 sites per module with support for a variety of stimulation schemes (biphasic/monophasic, bipolar/monopolar). We have developed software to generate multi-site stimulation commands for the IS-2B based on streaming data from artificial sensory devices such as cameras and microphones. For PC interfacing, we have developed a USB 2.0 microcontroller-based interface. Data is transmitted using frequency-shift keying (FSK) at 6/12 MHz to achieve a data rate of 3 Mb/s via a pair of rectangular coils. Power is generated using a Class-E power amplifier operating at 1 MHz and transmitted via a separate pair of spiral planar coils which are oriented perpendicular to the data coils to minimize cross-coupling. We have successfully demonstrated the operation of the system by applying it as a visual prosthesis. Pulse-frequency modulated stimuli are generated in real-time based on a grayscale image from a webcam. These pulses are projected onto an 11 × 11 LED matrix that represents a 2D microelectrode array.**

Keywords—**Neural stimulation, visual prosthesis, inductive wireless telemetry, sensory encoding, dual-carrier, multi-site, microelectrode array, frequency-shift keying, class-E amplifier**

I. Introduction

Electrical stimulation in the cochlea, retina, or sensory parts of the cerebral cortex has long been known to produce sensory perceptions which mimic natural stimuli [1]. However, only with recent advancements in microelectronics photolithography, and computing power have practical prosthetics that communicate directly with the central nervous system (CNS) through a large number of stimulating sites become feasible [2].

Many current stimulating implants have fewer than a dozen stimulation sites, and for some applications this number is sufficient. For example, after training, a patient with a cochlear implant can converse on the phone with as few as 6 stimulation sites. However, for a cortical visual prosthesis, it has been suggested that upwards of 625 sites must be stimulated in order to restore a functional sense of vision to the profoundly blind [3], [4]. Furthermore, neural information is generally encoded as frequency-modulated action potentials in the ~10-200 Hz range [5], and an implanted stimulator must either be capable of modulating input data and generating pulse trains in this range or the wireless link must provide enough bandwidth to allow "trigger" commands from an external controller to specify when and where each pulse should occur. Onboard modulation requires significantly less bandwidth to operate; however, it comes at the expense of much higher complexity, higher power consumption (and heat dissipation), larger implant size, and less flexibility and control over the modulation scheme. For these reasons, stimulation site selection and stimulus control in our system are handled externally on a command-by-command basis [11].

Because percutaneous cable connections are prone to infection and are highly uncomfortable for the patient, any practical long-term sensory neuroprosthetic implant must communicate wirelessly to the external part of the system. Furthermore, these devices require too much power to be operated solely from a long-life battery (as opposed to cardiac pacemakers). Therefore, power must also be transmitted via an inductive link to either power the implant continuously or charge an internal battery. To transmit power, a low carrier frequency is desirable to limit the level of electromagnetic energy absorption in the surrounding tissue. However, high data throughput requires a high carrier frequency. Therefore, using a single coil pair and carrier frequency to transmit both power and data leads to conflicting requirements [6]. To remedy this conflict, our system uses a dual-carrier inductive link with separate coils for power and data transmission developed in our lab by Atluri and Ghovanloo [7], [8].

The goals of this research are twofold. First, we present an extensible software and hardware platform, shown in Fig. 1, on which neurophysiological experiments can be carried out. A number of these experiments focus on developing models for sensory representation within the CNS [4], [9], [10]. The system presented here is a powerful tool for these kinds of studies as it abstracts away the complexities of the input source and stimulation hardware and allows neurophysiologists to focus solely on stimulation algorithm development. Second, we demonstrate the feasibility of 128-site frequency-modulated stimulation with 787.40 μs temporal resolution using a 3 Mb/s inductive wireless link. Our experiments focus on modulating real-time data from a webcam and projecting these onto a demonstrational LED matrix; however, any stimulator array could be used.

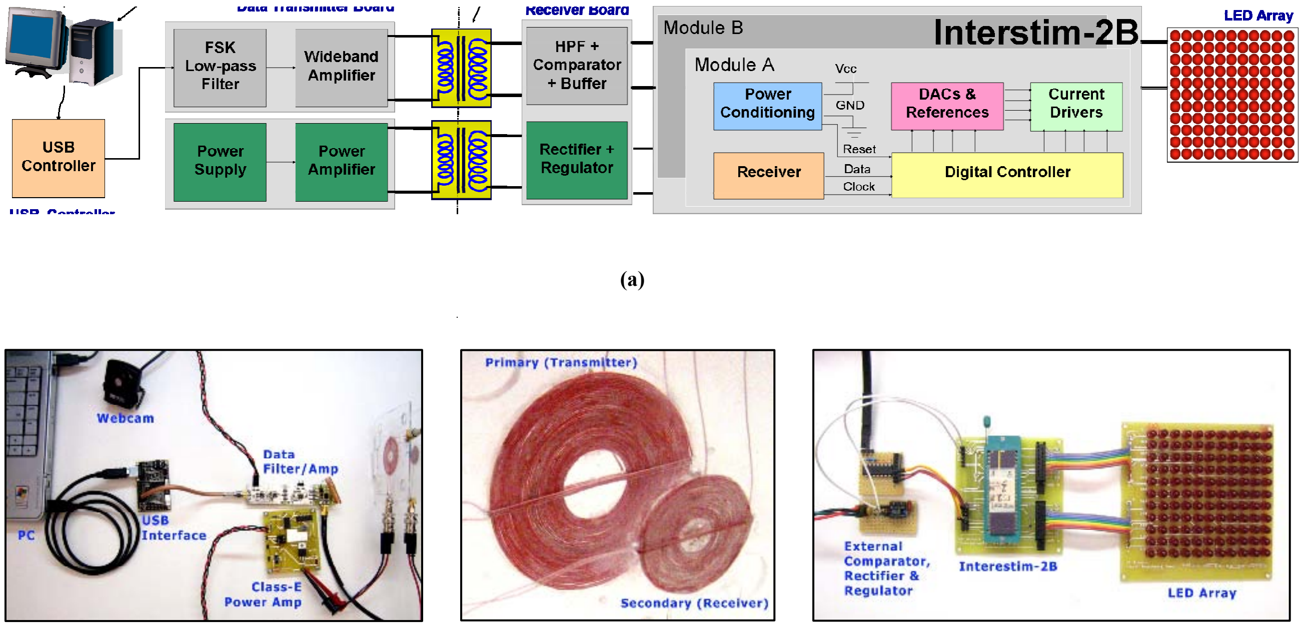


Fig. 1. (a) Block diagram of the system. (b) Transmitter components. (c) Power and data transmission coils. (d) Receiver and stimulator components

II. HARDWARE COMPONENTS

A. *Interestim-2B Microstimulator*

Our system is centered on the Interestim-2B (IS-2B), a 4.6 mm × 4.6 mm versatile CMOS microstimulator ASIC, fabricated in the AMI 1.5-µm standard CMOS process [11]. Each IS-2B module provides 32 independent stimulation sites which can each source or sink up to 270 µA. The chip is designed to provide maximum flexibility and allows for biphasic, charge-balanced stimulation as well as monophasic stimulation. Stimulation can occur between any two sites (bipolar) or between any site and a reference electrode (monopolar). Up to 64 modules (with unique addresses) can be connected in parallel to the same receiver coils for a maximum of 2048 sites. Each IS-2B chip contains two modules [11].

B. *PC Interface and Wireless Transmitter*

A USB 2.0 interface was developed for the PC interface because of its popularity, high throughput, reliability, and ease of use. The Cypress EZ-USB FX2 microcontroller provides a pass-through data bus which we configure to send a constant 24 Mb/s output data stream using an onboard 48 MHz timebase [14]. Our PC software converts each 18-bit IS-2B command into binary data representing FSK modulation at 6/12 MHz. This data is sent from the PC using 512 Byte "Bulk" USB transfers. Passing this digital output from the USB microcontroller through a DC level shifter and a 4-pole, Sallen-Key, low-pass filter with a cutoff frequency of 14 MHz results in a phase-coherent FSK modulated signal with 6 and 12 MHz carriers. This signal is then amplified using a wideband, high output drive current op-amp and transmitted through rectangular coils to the receiver. Careful attention has been given to matching the output of the drive amplifier with the data transmitter coil using a series-parallel LC-tank circuit [13]. A 1 MHz power carrier signal is also generated using a Class-E power amplifier and is transmitted to the implant via a pair of planar spiral coils [7], [8].

C. *Wireless Receiver*

Since the IS-2B was originally designed to receive both power and data through a single pair of coils [11], certain additional components had to be added to allow it to operate with two separate pairs of coils for data and power [7], [8]. In future generations of the Interestim system, these additional components will all be integrated on-chip. The additional off-chip circuitry includes an external rectifier and regulator to provide a separate 5V supply from the 1 MHz power carrier, an RC high-pass filter after the data coil to filter out interference from the power coil, and a high-speed comparator to convert the received differential FSK sine-wave carrier back to a single-ended digital CMOS-level serial data bit stream from which the IS-2B can derive its data and clock signals.

D. *LED Matrix*

An 11 × 11 LED matrix displays the current stimulus output from a single IS-2B chip (2 modules). This array is built to resemble a 2-D cortical stimulation array [2], [4].

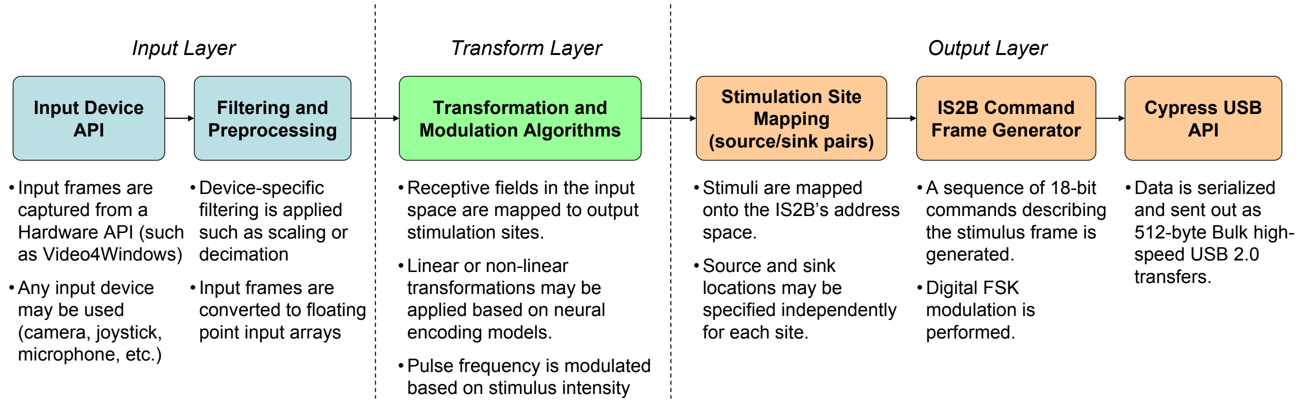


Fig. 2. Software flow diagram illustrating its major layers and components.

Each LED is connected to a unique pair of current drivers across 16 different drivers (8 per module). In other words, each LED represents a unique current path between two sites. A text script specifies the specific mapping of stimulus outputs to current paths. In our experiments, LEDs are mapped 1-to-1 with the 11 × 11 output image pixels. To increase the number of current paths—which may be desired with an actual cortical array where stimulation might be restricted to current flow between neighboring sites—more IS-2B modules could easily be added to the system.

III. Software Organization

The software, implemented in Visual C++, is organized into 3 distinct layers as shown in Fig. 2. This is in an effort to allow researchers to experiment with different transformation and modulation algorithms through a well-defined application programming interface (API) without having to deal with the underlying complexities of the input hardware and output stimulator command format. Currently the software supports input from only a camera or a stimulus input file, but future versions of the software will provide support for a larger variety of input devices.

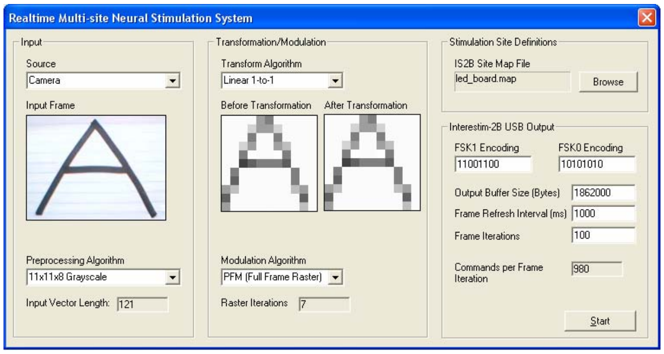
First, input data frames are captured from a webcam through a hardware API (in our case, Video4Windows). Filtering techniques are then applied to increase clarity and eliminate unwanted features from the input space [12]. In our experiments, we convert to grayscale and down-sample the input image at this stage. After filtering, data is passed into the transformation/modulation algorithm as a simple numerical array.

Transformation algorithms map receptive fields in the input space to output stimulation parameters. Receptive fields in a visual prosthesis application might include spatial, chromatic, or morphological components [4], while in a motor prosthesis application, they might include kinematic components (acceleration, velocity, etc.) [9]. Algorithms may be implemented directly in C++ or with the help of a tool such as MATLAB which provides the capability to expose functions to C++ applications. The system places no restrictions on what type of algorithm is implemented (linear or nonlinear). A variety of stimulus modulation schemes are possible (pulse-width, pulse-amplitude, pulse-frequency, etc.). For our experiments, we have chosen pulse-frequency modulation (PFM), since this is the principal encoding mechanism of neural data [5]. To perform PFM, the output space is rastered (sites are stimulated sequentially) M iterations per frame, where M is the number of iterations required to generate the lowest frequency pulse. Output pulses are generated at each site for some fraction of these iterations which is proportional to that site's output intensity.

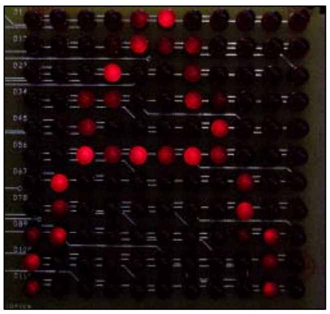
The output layer consists of a stimulus mapping function which, based on an input map file, translates each output index into an IS-2B source/sink driver pair (which consists of a module address, output channel, and stimulation site). A command frame generator then generates source/sink trigger commands based on the IS-2B command set [15]. Binary data is FSK modulated here at 6 and 12 MHz according to IS-2B's FSK modulation scheme, where logic "1" is represented by a 2-cycle 6 MHz square wave and logic "0" is represented by a 4-cycle 12 MHz square wave [13]. This data is then serialized into USB output packets. The USB microcontroller passes the received data directly to its output bus, after which it is DC level shifter, filtered, amplified, and transmitted across the data coils.

IV. Results

The system successfully achieved 3 Mb/s FSK data transfers from the USB interface to the implant via the inductive wireless data link. The two IS-2B modules reliably derived clock and data signals from the FSK input. Simultaneous PFM stimulation across 128 bipolar sites with a maximum pulse frequency of 10.31 kHz was successfully demonstrated. Since the maximum frequency for action potentials is about 200 Hz (limited primarily by the 5 ms axon refractory period) [5], we have substantially more bandwidth available for driving even more sites (i.e. an image with a higher resolution than 11 × 11). Due to imperfections in the construction of data and power coils and the proximity of the power carrier frequency (1 MHz) to



(a)



(b)

Fig. 3. (a) Windows GUI showing different configuration options. In this example, the handwritten letter "A" was captured with a webcam and mapped onto the 11 × 11 output space as an 8-level grayscale image. (b) The resulting output on the LED matrix. Brighter pixels correspond to sites with higher stimulation frequency.

data (6/12 MHz), the amount of power interference in the received data was more than what a single-pole RC filter could suppress. Hence, we were not able to simultaneously transmit data and power for an extended period of time. However, we are working to widely separate power and data carries to 125 kHz and 25/50 MHz, respectively, to enable reliable simultaneous power and data transfers [7].

Fig. 3a shows the GUI, while the software processes an image of the letter "A" that is handwritten on a piece of paper and placed in front of the camera. The GUI generates an 8-level grayscale 11 × 11 image with no transformation further applied. This frame translates to 980 19-bit IS-2B commands, which means that one iteration of a full image frame takes 6.21 ms at 3 Mb/s. This provides a maximum pulse frequency of 10.31 kHz, or alternatively, a 787.40 µs temporal resolution for monophasic pulses. Biphasic (charge-balanced) pulse temporal resolution would be approximately twice this amount (~1.57 ms), because the number of required commands roughly doubles. Fig. 3b shows the resulting image on the LED display, where higher frequency stimuli can clearly be distinguished as brighter pixels.

The Cypress USB interface has functioned very reliably throughout our experiments. On a 2 GHz Athlon-64 PC with 1 GB RAM, we were capable of streaming data at a continuous rate of 12 Mb/s, which is enough to generate 6 and 12 MHz FSK carriers (3 Mb/s effective data rate). Frames are updated at approximately 3.23 Hz by transmitting bursts of commands. The primary cause of slow rate is in the inefficient data transfer mechanism between our software and Cypress's USB API, and we hope that by making software improvements we can achieve a refresh rate comparable to the human eye's natural rate of about 60 Hz.

V. Conclusion

The multi-channel, wireless neural stimulation system presented here has been successfully demonstrated as a high data rate visual prosthesis system capable of driving a large number of sites. We have developed software with a high level of flexibility, which can be adapted to a variety of applications. This system is easy to use and is compatible with any standard PC though a USB 2.0 interface. Work is underway to provide support for USB-equipped handheld computers as well. In the near future we plan to test the system *in vivo* with an actual microelectrode array.

References

[1] J. S. Yeomans, *A brief history of brain stimulation. In: Principles of brain stimulation.* New York: Oxford University Press, 1990. pp. 3-19.

[2] K.D. Wise, "Silicon microsystems for neuroscience and neuroprostheses,". *IEEE Eng. in Med. and Biol. Magazine*, vol. 24, issue 5, Sept.-Oct. 2005, pp. 22-29.

[3] K. Cha, K.W. Horch, and R.A. Normann, "Simulation of a phosphene field based visual prosthesis," *Proc. IEEE Intl. Conf. on Systems, Man, and Cybernetics,* Nov. 4-7, 1990, pp. 921-923.

[4] R.A. Normann et al., "High-resoultuion spatio-temporal mapping of visual pathways using multi-electrode arrays," *Vision Research*, vol. 41, pp. 1261-1275, 2001.

[5] F. Rieke, et al., "*Spikes: Exploring the Neural Code,*" Cambridge, MA: MIT Press, 1999.

[6] W. Liu, et al, "Implantable Biomimetic Microelectronic Systems Design: Systems, Components, and Signal Processing," *IEEE Eng. in Med. and Biol. Magazine*, Sept./Oct. 2005.

[7] S. Atluri and M. Ghovanloo, "Design of a wideband power-efficient inductive wireless link for implantable biomedical devices using multiple carriers," *Proc. 2nd Annual IEEE Intel. Eng. in Med. and Biol. Conf. on Neural Eng.*, March 2005, pp. v-ix.

[8] S. Atluri and M. Ghovanloo, "A wideband power-efficient inductive wireless link for implantable microelectronic devices using multiple carriers," to be presented at the *IEEE Intl. Symp. on Cicuit. and Sys.*, May 21-24, Kos, Greece.

[9] S. Shoham, et al., "Statistical encoding model for a primary motor cortical brain-machine interface," *IEEE Trans. Biomed. Eng.*, vol. 52, no. 7, July 2005.

[10] B.M. Dow, R.G. Vautin, and R. Bauer, "The mapping of visual space onto foveal striate cortex in the macaque monkey," *Journal of Neuroscience*. vol. 5, no. 4, April 1985.

[11] M. Ghovanloo and K. Najafi. "A modular 32-site wireless neural stimulation microsystem," *IEEE Journal of Solid-state Circuits*, vol. 39, no. 12, Dec. 2004, pp. 2466-2457.

[12] W. Liu, W. Fink, M. Tarbell, and M. Sivaprakasam, "Image processing and interface for retinal visual prostheses.," *IEEE Intl. Symp. Circuits and Systems,* 23-26 May, 2005, pp. 2927-2930.

[13] M. Ghovanloo and K. Najafi. A wideband frequency-shift keying wireless link for inductively powered biomedical implants," *IEEE Trans. Circuits and Sys.*, vol. 51. no. 12, Dec. 2004, pp. 2374-2483.

[14] Cypress EZ-USB FX2 microcontroller data sheet, [Online]. Available: www.cypress.com.

[15] K. Najafi and M. Ghovanloo, "A multichannel monolithic wireless microstimulator," *IEEE 26th EMBS Conf.*, pp. 4197-4200, Sep. 2004.