A Programmable Neural Interface for Investigating Arbitrary Stimulation Strategies

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Abstract

This paper presents a microcontroller-based neural interface capable of producing arbitrary current-mode waveforms for use in developing and evaluating electrical stimulation strategies. The presented application-specific customisation focuses on charge-balanced biphasic waveforms delivered to a bipolar electrode configuration, although the hardware is capable of interfacing with other electrode topologies and/or producing different waveform profiles. The system comprises of a MATLAB-based GUI for specifying the stimulus profiles and delivery parameters, a USB link to transfer the data between the PC and embedded controller, and the stimulator hardware, which, once programmed can operate as a portable battery-powered module.

1. Introduction

Neural prostheses typically utilise *electrical stimulation* to interface electronic devices to the nervous system. Medical devices including cochlear implants and Deep Brain Stimulators can be used to provide rehabilitation for hearing loss and conditions like Epilepsy, Parkinsons and Dystonia. In the long term, key factors like neural fatigue, electrode degradation/stability, stimulation efficiency and input dynamic range greatly affect the performance of a stimulator [1]. Thus, developing effective stimulation strategies to achieve optimal performance is crucial for any neural prosthesis deployed chronically.

More recently, a number of emerging medical devices interface with the central nervous system (CNS) via the 10th cranial (vagus) nerve [2] using non-penetrating (e.g. cuff) electrodes. This is because this is the only cranial nerve that extends from the brainstem via the neck to the chest and abdomen, and contains both afferent and efferent nerve fibres. However, a key challenge is to develop selective stimulation methods, i.e. to achieve unidirectionality, fibre- and fascile-type selectivity and avoid unintentional excitation [3,4].

Therefore, the development of novel stimulation strategies is crucial to both improving neuroprosthetic technology and associated therapies, allowing neurostimulators to intergrate into mainstream medical practice. The work reported herein supports this goal by providing a stimulation platform for developing novel strategies. This provides a user-friendly, versatile platform for scientists to investigate stimulation strategies with improved selectivity, efficiency and robustness.

The vast majority of neuroscientists and bioengineers currently use bulky instrument-based stimulation apparatus. Custom platforms developed include ASIC-based devices for multi-channel stimulation [5,6] and discrete component, i.e. PCB-based devices [3,7] for in-vivo deployment. Although such devices are both portable and reconfigurable, they are not currently commercially-available and, most importantly, have limited versatility in stimulation parameters. This work is therefore aimed towards producing an open-access research tool for stimulation strategy development, progressing apparatus previously reported [4].

2. Stimulation Platform

The top-level system architecture illustrating the main components is shown in Figure 1. The system consists of two main sub-systems: A PC-based platform for operating the GUI software (to specify stimulation parameters) and the stimulator hardware (to generate in stand-alone the required stimulus waveforms):

2.1. PC-based Stimulus Profile Editor

This is centred on a GUI developed in MATLAB to enable rapid deployment of commonly used waveforms types in addition to the option for defining truly arbitrary waveform profiles. Preconfigured waveform

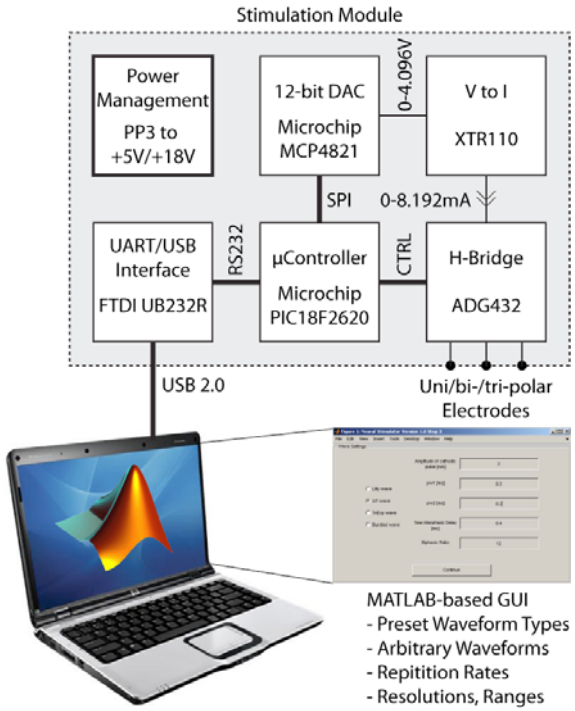


Figure 1. Basic system architecture illustrating main components.

profiles include the Lilly [3], quasi-trapezoidal, tri-exponential decay (tri-exp) and bursting strategies (See Figure 2) [8]. Tuneable parameters include the various current amplitudes, pulse durations, the inter-phasic delay, biphasic (asymmetry) ratio, and repetition rate. Alternatively there is the ability to import an arbitrary waveform (CSV file). The software then generates the stimulus profile as a block of data (see Table 1) for upload to the stimulator (via USB).

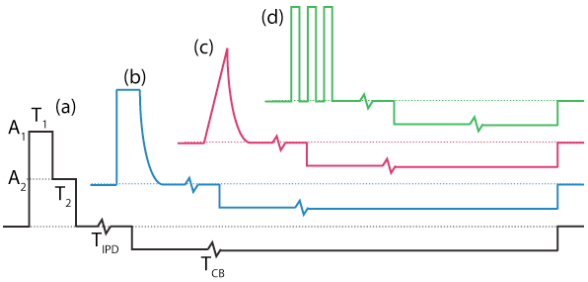


Figure 2. Preconfigured stimulation profiles (not to scale): (a) bi-level Lilly, (b) quasi-trapezoidal, (c) tri-exp, and (d) bursting.

2.2. Portable Arbitrary Stimulator

The portable arbitrary stimulator has been prototyped at PCB-level based on components listed in Figure 1. Key design features are outlined below:

- **Power Supply:** To achieve an isolated power supply and portability, the device is powered from a standard PP3 (9V) battery. The logic (5V) and stimulation (18V) supplies are generated using a linear regulator (LM117) and switched capacitor charge pump (TC962) respectively.
- **Microcontroller:** The stimulator is based on the Microchip PIC18F2620 microcontroller. Key features include the 64K Flash EEPROM (Program memory) and 4KB RAM (Stimulation buffer), UART (for serial comm.), SPI (for DAC) and x4 PLL (for 40MHz crystal-derived clock).
- **UART Interface:** We have used the UB232R module (based on the FTDI chipset) to achieve serial connectivity via the USB 2.0 interface. This is used only to upload waveform profiles.
- **DAC:** The voltage output is generated using a Microchip MCP4821 serial (SPI) DAC (12-bit) with internal reference and x2 selectable gain.
- **V-to-I:** The voltage to current conversion is achieved using the TI Burr-Brown XTR110 Current converter. The target transconductance is 2mS, translating a DAC output range of 0-4.096V to a stimulus range of 0-8.192mA.
- **H-bridge:** This configuration is implemented using the ADG432 switch network to generate the biphasic waveform by reconfiguring the bipolar electrodes. This technique vastly improves current matching between anodic and cathodic pulses (if generated using independent sources) due to reuse of same source for both phases. Current mismatch (i.e. charge imbalance) is therefore entirely dependent on clock jitter (20ppm) and DAC/V-to-I non-idealities (13-bit).

The microcontroller control flow for the stimulator operation and PC communication is detailed in the flow chart shown in Figure 3. There are two modes of operation: USB uplink and stimulation playback.

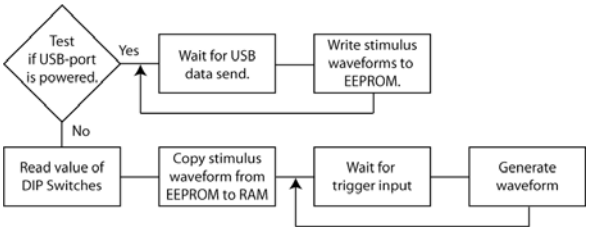


Figure 3. Control flow for stimulator hardware

The communication protocol for transferring the waveform profiles from PC to stimulator is given in Table 1. Upon transmission, the data is stored in the 32-64Kb region of flash, (0-32Kb is allocated for program memory). This allows for up to 128 waveforms to be stored in non-volatile memory. The active waveform is selected via DIP switches on the PCB.

Table 1: Comms Header (MATLAB to Stimulator)

Pos.	Description	Type (Range)
1	Waveform ID	1 byte (0-127)
2	Cathodic pulse duration	1 byte (0-255)
3	Cathodic amp. [1:120]	Int16 (0-8192)
243	Inter-phasic delay	Int16 (0-65535)
245	Anodic pulse duration	Int16 (0-65535)
247	Anodic pulse amp.	Int16 (0-8192)
249	Anodic pulse suffix amp.	Int16 (0-8192)
251	Inter-pulse delay (i.e. rate)	Int16 (0-65535)
253	Repetitions (0=cont.)	Int16 (0-65535)

3. Prototype & Measured Data

The prototype device is shown below in Figure 4. This has been designed in two modular subsystems; the first (left) contains the USB-UART interface, microcontroller and DAC. The second (right) contains the battery, power management, V-to-I, and H-bridge.

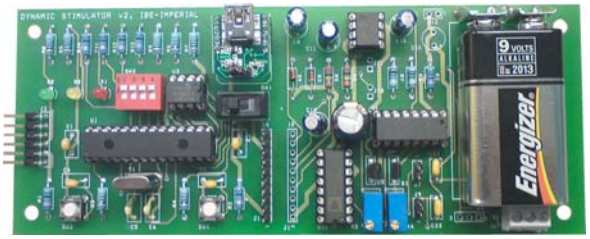


Figure 4: Prototype portable arbitrary stimulator.

The microcontroller has been configured to generate a burst, tri-exp and Lilly waveforms in sequence with 8mA cathodic pulse amplitude. Initial results have been measured using a *LeCroy WavePro 7300A* oscilloscope, shown in Figure 5.

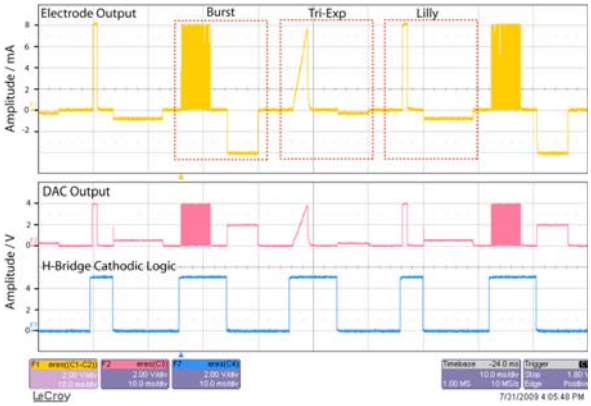


Figure 5: Measured current output into a 1KΩ dummy load (top). Also shown is the DAC output and H-bridge logic control for cathodic phase.

The total current consumption of the device is measured to be a maximum of 38mA (using full scale waveforms, i.e. 8mA cathodic pulses). This translates to a battery life of at least 30-31 hours (typical PP3 capacities up to 1200mAh- eg. Ultralife U9VL-J).

Although dynamic charge balancing strategies have not yet been implemented, the developed hardware is capable of sampling the electrode potentials (via the internal 10-bit ADC) and therefore closed-loop balancing can be implemented via firmware updates. At present, the charge balancing resolution is limited by the DAC resolution, V-to-I converter slew rate and microcontroller clock stability. This comes to approximately 50-500pC (depending on configuration and assuming good electrode stability). For example, a cathodic pulse of 1mA amplitude and 250µs duration would deliver 250nC and thus open loop charge balancing would achieve 0.02-0.2%. Additionally, series coupling capacitors are selectable to block net DC charge transfer.

4. Summary and Conclusions

In summary, we have developed a generic platform for arbitrary waveform generation for electrical (current-mode) stimulation. The interface has been designed to meet the specifications outlined in Table 2.

Table 2: Summary of technical specifications

Parameter	Value	Units
Cathodic Pulse Duration	0.02-1.2	[ms]
Interphasic Delay	0-1	[ms]
Time Resolution	10	[µs]
Amplitude Range	8.192	[mA]
Amplitude Resolution	10	[µA]
Repetition Frequency	10-100	[Hz]
Biphasic Ratio (Asymmetry)	10-50	-
Electrode/Electrolyte Imp. (Z)	1-4	[KΩ]

Although the current range will allow for current outputs of up to 8mA, the voltage compliance (18V) will be the limiting factor for larger electrode impedances. However, in applications using electrodes of higher impedance, electrode geometries are generally smaller and thus stimulation tends to be at closer proximity (to the target) and therefore require lower stimulus magnitudes. For applications requiring large stimulus magnitudes into high impedance electrodes, two PP3 batteries can be series connected to boost the voltage compliance up to 36V (i.e. 8mA into 4 KΩ).

In its current state, this platform provides a powerful stimulation research tool suitable for a number of applications. It is our intention to make both the hardware (stimulator PCB design) and software (firmware and GUI) freely accessible for other groups to use and customise to their requirements. This will be available via our institutional web portal (Institute of Biomedical Engineering, Imperial College London – http://www.imperial.ac.uk/biomedeng).

5. Literature

[1] K. W. Horch, G. Dhillon, "Neuroprosthetics: Theory and Practice", World Scientific, 2004.

[2] www.vnstherapy.com, Cyberonics Incorporated.

[3] M. Bugbee, et al., "An implant for chronic selective stimulation of nerves", Medical Engineering & Physics, 23, pp. 29-36, 2001.

[4] V. Woods, et al., "A Reconfigurable and Automated System for the Study of Stimulus Waveform Parameters", Proc. IFESS, 2008.

[5] www.neurotech.be, OPTIVIP-ASIC, NeuroTech

[6] T. G. Constandinou et al,. "A partial-current-steering biphasic stimulation driver for vestibular pros", IEEE TBCAS, 2 (2), 2008.

[7] H. Sha, et al., "A microcontroller-based implantable nerve stimulator used for rats", Proc. IEEE EMBC, pp. 6176-6179, 2005.

[8] W. M. Grill et al, "Stimulus Waveforms for Selective Neural Stimulation", IEEE EMBS magazine, pp. 375-385, 1995.