5th Quarterly Progress Report

Nov 1 2003 to Jan 31, 2004

Neural Prosthesis Program Contract N01-DC-02-1006

The Neurophysiological Effects of Simulated Auditory Prosthesis Stimulation: Stimulator Switch

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Abstract

This Quarterly Progress Report presents our progress in the 5th quarter of this contract. During this period, we have made progress in following areas: 1) We have fabricated six additional multi-channel intracochlear implants designed specifically for the guinea pig. Five of these electrodes have been sent to collaborators (John Middlebooks, at the University of Michigan; Johan Frinjs at the University of Leiden; Charles Miller at the University of Iowa; Dave Edell, at Inner Sea Technologies Inc.; Dan Merfeld, at Harvard Medical School), who have made urgent requests for them. 2) Some of these implants incorporated several alternative design features. Using these electrodes, we conducted a series of physiological experiments in acutely deafened guinea pigs tested the effects closely spaced longitudinally oriented bipolar electrodes and radially oriented bipolar electrode on neural activity evoked in the auditory system. 3) During the first phase of several of these experiments, prior to deafening the animals, we have extended our studies of acoustic simulations of channel interaction in intracochlear electrical stimulation (ICES) using two-tone interactions in a forward masking paradigm. The preliminary results of these acoustic experiments and the electrical stimulation experiments were presented at the Midwinter meeting of the Association for Research in Otolaryngology (Bonham et al., 2004). 4) In the second phase of each of these experiments, we have examined electrical channel interactions using our multichannel guinea pig implant implants activated with pulse trains. 5) During the month of January, Dr. Snyder presented seminars describing our auditory prosthesis work at the Kresge Hearing Research Institute at University of Michigan, Ann Arbor, MI and at the Eaton-Peabody Lab, Massachusetts Eye and Ear Infirmary, Boston, MA. 6) During his 10 day stay at the Kresge Hearing Institute, Dr. Snyder conducted a series of 7 experiments examining the effects of forward and simultaneous masking using intracochlear electrical stimulation in the laboratory of Dr. John Middlebrooks. Dr Middlebrooks, a consultant on this contract, spent two months last summer conducting experiments in the Epstiein Lab. His family commitments prevented him from continuing these experiments at UCSF. Therefore, Dr. Snyder traveled to his laboratory where we conducted 7 guinea pig experiments in two weeks. The results of Some of these experiments will be reported at the Midwinter Meeting of the Association for Research in Otolaryngology (Middlebrooks et al, 2004). 7) While staying in Ann Arbor, Dr. Snyder conferred with Mr. Chris Ellinger, the chief electrical engineer at the Kresge Hearing Research Institute, regarding the construction of a 32 channel headstage and pre-amplifier for the Epstein Lab. Mr. Ellinger agreed to build these devices and to build an eight channel constant current stimulator for our lab. Mr. Ellinger agreed to supply these devices at cost to the Epstein Lab. 8) While staying 3 days in Boston, Dr. Snyder assisted Mr. Zachary Smith and Dr, Bertrand Delgutte in a bilateral intracochlear electrical stimulation experiment. He also conferred with Drs. Bertrand Delgutte, Donald Eddington and Daniel Merfeld and agreed on collaboration with them. In this collaboration, the Epstein Lab personnel would provide technical assistance in the production of cat intracochlear electrodes and monkey vestibular electrodes. 8) During this period, we (Dr, Ben Bonham) completed the design, construction and testing of a high speed multichannel switch that will allow us to switch between the inputs of up to 4 constant stimulators and the outputs of up to 16 intracochlear electrodes. This switch is required for the multichannel speech and channel interaction experiments projected for years 3 and 4 of this contract. The detailed description of this switch is contained in the body of this progress report.

Introduction:

This section describes the design and use of an isolated analog switch module suitable for switching the output of a single current stimulator to any of eight bipolar (or sixteen monopolar) cochlear implant channel destination electrodes. Several of these switch modules may be used together to expand the number of stimulators and/or destinations available for switching. The switch module is specifically designed to accommodate the relatively high compliance voltages used in our implant physiology research (up to +/- 80 V), and is able to switch a stimulator between destination channels with a switching time of less than 100 µs. This device was designed and constructed in order to allow time-multiplexing of one isolated high-voltage current stimulator, which is a relatively expensive device, among several implant channels and channel configurations. The effort was crucial to this contract since we are studying the effects of channel interaction, and consequently needed the ability to stimulate several channels and/or channel configurations during one experimental series or run. A benefit of incorporating this switch module in the experimental work is that unused implant channels are disconnected from any stimulator (connected through very high impedances, actually), which consequently reduces recording noise (personal communication, Roger Miller). While it would be possible to rewire the current stimulator and implant channels by hand between runs during an experiment, there is less room for error if this rewiring is done under software control. Further, better controls for experiments are possible because trials with different channel configurations can be interleaved within an experimental run. Interleaving trials reduces the likelihood of confusing time-related effects (e.g., those due to changing level of anesthesia) with channel configuration effects.

Use:

A single switch module can be used to stimulate in bipolar mode in which the stimulator *source* [1]and *sink* each can be connected to any of eight implant electrodes (Figure 1). The module is intended to switch the stimulator between destination electrodes at times when no current is flowing (i.e., between stimulus pulses, rather than during active current flow through implant destination electrodes). During construction, installation of eight jumper wires determines whether the module will be configured in monopolar or bipolar mode. Four other jumpers determine the range of board addresses. The following describes use of a module configured in bipolar mode and that has all addresses set to the "low" range. Jumper settings are described later. Each switch module printed circuit board has three headers: one input header (#1) which is connected to the current stimulator (two wires -- one to connect to the stimulator *source*, and one to the stimulator *sink*), one output header (#2) which is connected to the implant (sixteen wires, eight of which are used in the bipolar configuration), and one digital control header (#3) that includes eight digital control wires along with power and ground for the digital logic. In practice, the two-wire input is connected to the *source* and *sink* conductors of an isolated current stimulator. Eight output wires are connected to eight electrode conductors of a multi-electrode cochlear implant, and the digital control port is connected to a

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[1] With goals of achieving consistency and clarity, the following nomenclature is used: The stimulation current is provided by a (current) stimulator, which has one current source wire and one current sink wire. The output of the switch (board module) is connected to an implant, which incorporates one or more (destination) electrodes; each destination electrode can be considered a source or a sink of the current passing into the cochlea from the implant.

controlling computer (which could be, e.g., a computer parallel port, a dedicated DIO port from a National Instruments interface card, or the digital output port of a TDT RP2 real time processor). Headers #2 and #3, which fit standard ribbon cable connectors (i.e., pin spacing is 0.10") are described in Figure 2. The third header (#3) is used to connect to the digital controller and to provide power to the board logic. The digital control should have 8 TTL outputs (D0-D7). These should be settable, but need not change during stimulation unless one wants to change the implant electrode configuration. In the basic bipolar configuration, the low-order bits (D0-D3) determine which of the eight implant electrodes (E0-E7) is connected to STIM0 of header #1 (the stimulator *source*), and the high-order bits (D4-D7) determine which of the eight implant electrodes (E0-E7) is connected to STIM1 of header #1 (the stimulator *sink*). A 5-volt power source should also be connected here to provide power for the digital logic on the board. Note that connection of one of the implant electrode wires (e.g., E7) to an extracochlear return wire, rather than an implant electrode, allows for software selection of 7 bipolar channels and 7 monopolar channels.

Digital selection of implant channels:

The implant (destination) source channel is determined by levels of D3-D0 of the digital control port. (D3 must be TTL "0", =0V, to select any channel on a board configured for "low" addresses.) D2-D0 determine which of the eight implant channels the stimulator *source* is connected to, using a standard binary encoding (i.e., D2D1D0 = 000 -> channel 0, D2D1D0 = 110 -> channel 6, etc). The implant (destination) sink channel is determined by D7-D4. (D7 must be TTL "0" to select any channel on a board configured for "low" addresses.) D6-D4 determine which of the eight implant channels the stimulator *sink* is connected to, using a standard binary encoding (i.e., D6D5D4 = 110 -> channel 6, etc). So, for example, to stimulate in bipolar mode with implant channel 0 connected to the stimulator *source* and implant channel 1 connected to the stimulator *sink*, the digital port should be set to $0001{,}0000_2$ ($= 10_{16} = 16_{10}$). To stimulate in bipolar mode with implant channel 1 as the source and implant channel 0 as the sink, the digital port should be set to $0000{,}0001_2$ ($= 01_{16} = 01_{10}$). To stimulate in bipolar mode with implant channel 4 as the source and implant channel 7 as the sink, the digital port should be set to $0111{,}0100_2$ ($= 74_{16} = 116_{10}$). A MATLAB code fragment to select implant channel electrode configuration is shown below:

```
% encode destination channel settings for a bipolar switch module
% the switch module is configured for the low address range
% the module is controlled by the digital port in a TDT RP2
channelSelect1 = 16*(3-1)+(4-1); % this is bipolar <3,4> (range is 1-8)
noPOSError = 255;
noPOSError = noPOSError & invoke(RP2_1,'SetTagVal','channelSelect1',...
        channelSelect1);
if ~noPOSError,
                error('error setting channels in RP2');
        end
```

Use with Two Modules:

16 bipolar channels: A second board module, with address jumpers installed corresponding to the "high" address range, can be used in conjunction with the module in bipolar configuration described above (configured for the "low" address range) to switch the output of a single current stimulator to any of sixteen implant channel electrodes (Figure 3). In this configuration, the single current stimulator is connected in parallel to header #1 of both boards (i.e., the *source* wire from the stimulator is connected to STIM0 on both boards, and the *sink* wire from the stimulator is connected to STIM1 on both boards). The digital input is connected in parallel to header #3 of both boards. There should be two separate output connectors from the output headers (#2) of the two boards to the implant. Each of the output headers should connect to a different set of eight implant electrodes. A simple way to accomplish this is to put two 16-pin cable connectors onto one 16-wire ribbon cable while offsetting the end-most connector by one wire (by, e.g., peeling off conductor #1 for a short distance -- see Figure 4). If the end-most connector is inserted into the header on the second board, and the other connector is inserted into the header on the original board, the odd-numbered wires in the cable will be switched in by original board module ("low" addresses), and the even-numbered wires by the second board module ("high" addresses). The current source destination electrode is still determined by D3-D0, but now D3 determines whether the source electrode will be one of those connected to the original board (if D3="0") or the second board (if D3="1", = 4-5V). Similarly, the current sink destination electrode is still determined by D7-D4, while D4 determines whether the sink electrode will be one of those connected to the original board (D7="0") or the second board (D7="1"). Thus, setting the digital port to $1111,0000_2$ (= $F0_{16}$ = 240_{10}), will select E7 of the second board and E0 of the first board as current sink and source channels.

Seven pseudo-tripolar (pseudo-quadrupolar) channels: A second board module, with address jumpers installed corresponding to the “low” address range, can be used in conjunction with the original module in bipolar configuration (also configured for the "low" address range) to stimulate any three of eight destination channels in “pseudo-tripolar” mode (Figure 5). In pseudo-tripolar mode, current entering the cochlea on a center source channel is returned via two flanking sink channels that are shorted together. In this configuration, a single current stimulator is connected to header #1 of the original board . Pins STIM0 and STIM1 of header #1 on the second board are shorted together. Headers #2 are connected in parallel to the implant (e.g., by installing two connectors onto a single ribbon cable with no offset). Connections to header #3 of the original board come from one digital computer port, and connections to header #3 on the second board come from a **second digital port**. The current source channel is determined by D3-D0 of the first digital port (D3 must be “0”). One sink channel is determined by D7-D4 of the first digital port (D7 must be “0”). The second board is used to short the two sink channels together. The second sink channel is determined by D3-D0 of the second digital port (D3 must be “0”). Bits D7-D4 are set to select the same destination channel as bits D7-D4 of the first digital port (D7 must be “0”). So, for example, setting digital port 1 to $0100,0011_2$ (= 43_{16} = 67_{10}) selects E3 as the destination channel for the stimulator *source* and E4 as one destination channel for the stimulator *sink*. Setting digital port 2 to $0100,0010_2$ (= 42_{16} = 66_{10}) selects E4 and E2 as the destination channels to short together (because STIM0 and STIM1 on this board are shorted). A portion of the current entering the cochlea on channel E3 will return on E4, and the remainder will return on E2. The proportion that returns on each channel will depend upon the electrode impedances.

Seven tripolar (quadrupolar) channels: A second board module, with address jumpers installed corresponding to the “low” address range, can be used in conjunction with the module in bipolar configuration described above (also configured for the "low" address range) to stimulate any three of eight destination channels in tripolar mode (Figure 6). In tripolar mode, current entering the cochlea on a center source channel is returned via two flanking sink channels that are independent. In this configuration, one current stimulator is connected to header #1 of the original board . A **second current stimulator** is connected to header #1 of the second board. Connections to headers #2 are as described in the previous section. Connections to header #3 of the original board come from one digital computer port, and connections to header #3 on the second board come from a **second digital port**. The current source channel is determined by D3-D0 of the first digital port and D3-D0 of the second digital port (D3- D0 on both ports must be the same, and D3 must be "0"). One sink channel is determined by D7-D4 of the first digital port (D7 must be "0"). The second sink channel is determined by D7-D4 of the second digital port (D7 must be "0"). So, for example, setting digital port 1 to $0100{,}0011_2$ (= 43_{16} = 67_{10}) selects E3 as the destination channel for the current source and E4 as one destination channel for the current sink. Setting digital port 2 to $0010{,}0011_2$ (= 23_{16} = 35_{10}) selects E2 and E3 as the two destination channels for the current sink and source of the second stimulator. Currents from the two current stimulators will sum to provide current to channel E3. A portion of the current will return on channel E2, and a portion will return on E4. The exact proportion returning on each will depend on the current levels from the two stimulators.

Monopolar configuration: The switch module can be configured to allow monopolar stimulation on any of sixteen destination electrodes (Figure 7). Two modules, each configured in monopolar mode with appropriate address configurations, can be used to stimulate in bipolar mode on any of sixteen destination electrodes using one digital control port. Three modules, each configured in monopolar mode with appropriate address configurations, can be used to stimulate in tripolar mode on any of sixteen destination electrodes using two digital control ports.

Use with multiple modules: Additional modules can be used to increase the number of destination channels available for switching. For example, four boards configured as follows will allow use of a single current stimulator to stimulate a single pseudo-tripolar channel configured from any three of sixteen destination electrodes: Two board with addresses jumpered "low" (boards #0 and #1) and outputs in monopolar configuration and two boards with addresses "high" and outputs in monopolar configuration (boards #2 and #3). Header #1 pins STIM0 and STIM1 are shorted together on boards #1 and #2, and these in turn are shorted together (all four pins are shorted together). Header pins STIM0 on boards #0 and #3 are both connected to the stimulator *source*, and header pins STIM1 on boards #0 and #3 are both connected to the stimulator *sink*. The first digital port is connected in parallel to header #3 on boards #0 and #3, and the second digital port is connected in parallel to header #3 on boards #1 and #2. Finally, headers #2 on boards #0 and #1 are connected together in parallel and connected to implant destination channels 0-7, and headers #2 on boards #2 and #3 are connected together in parallel and connected to implant destination electrodes 8-15 (this can be accomplished using an offset ribbon cable). Bits D7-D0 of the second digital port determine the two destination sink channels of the pseudo-tripolar configuration. Bits D3-D0 of the first digital port determine the destination source channel, and bits D7-D4 of the first digital port must be set to the same value as D7-D4 of the second digital port.

Hardware description & configuration:

The schematic diagram for the switch module is shown in Figures 9a and 9b. The basic devices used for switching are optically isolated high-voltage bidirectional solid state switches (U2-U9, U11-U18; AQV225N Aromat PhotoMOS relays). Hardware decoders (U1, U10; 74HC138 decoder) are used to select switch configurations based on control signals applied to the digital port. Standard power supply bypass capacitors (C10, C20) reduce susceptibility to supply transients, and standard pull-up resistors (RN4) set the default input levels for the decoders to logical "1". The turn-on and turn-off times for the photomos relays are dependent on the forward current through the input photodiodes. To reduce turn-on time, the forward current should be large. However, a large forward current increases the turn-off time. To accommodate a requirement for large forward current for fast turn-on, and small forward current for fast turn-off, an RC network (RN1-RN3, C2-C9, C11-C18), is used to provide forward current for the photodiodes. Examining specifically the photodiode input to U11, when the decoder output /Y0 from U10 is high, no current flows through the photodiode, the voltage at the junction of C18 and RN1 is $+V_{CC}$ and capacitor C18 is charged to 0 V. When decoder output /Y0 drops to V_{OL}, the forward current is initially $(V_{CC}-V_f-V_{OL})/RN1$ (approximately (5-4.3-0.1)/100, or 42 mA), which is compatible with a short turn-on time. While the photodiode is turned on, capacitor C18 gradually charges to $(V_{CC}-V_f)*RN2/(RN1+RN2)$ (approximately 3.8 V) with an approximate time-constant of C*RN1*RN2/(RN1+RN2) (45 μs), resulting in a forward current of $(V_{CC}-V_f- V_{OL}-V_{C18})/100$ (4 mA) which is compatible with a short turn-off time. While the photodiode is turned off, capacitor C18 (dis)charges to 0 V with a time-constant of C*RN2 (0.5 μs). Measured minimum turn-on and turn-off times are below 100 μs.

Monopolar/bipolar jumpers: Jumpers JP1-JP8 are used to set the module to monopolar (Figures 8 & 9) or bipolar mode. Relays U11-U18 are used to connect the current stimulator *sink* wire (header pin STIM1) to exactly one of the output header pins E0-E7 (connected to the cochlear implant). For 8-channel bipolar mode, jumpers JP1-JP8 are installed so that the output of the relays U2-U9 are connected to output header pins E0-E7. In this case, the relays U2-U9 are used to connect the current stimulator *source* wire (header pin STIM0) to exactly one of the output header pins E0-E7. In this case, the current stimulator *source* can be connected under software control to any of eight implant channels. The *sink* of the same current stimulator can simultaneously be connected under software control to any of those eight implant channels. For 16-channel monopolar mode, jumpers JP1-JP8 are installed so that the output of the relays U2-U9 are connected to output header pins E8-E15 (which are connected to the cochlear implant). In this case, the *sink* of the current stimulator should be connected to an extracochlear return electrode, and the *source* of the current stimulator should be connected to the two header pins STIM0 and STIM1. The *source* of the stimulator can then be connected under software control to any of 16 implant channels in monopolar mode.

Board address jumpers: Jumpers JP9 and JP10 identify the "address" range for the module. If jumper JP10 is installed in the "left" position (nearer to the digital input header), decoder U10 is selected when digital input D7 is logical "0". If jumper JP10 is installed in the "right" position (away from the digital input header), decoder U10 is selected when digital input D7 is logical "1". Similarly, jumper JP9 determines whether a logical "0" or "1" on digital input D3 selects decoder U1. A decoder must be selected for the current stimulator to be connected to any implant destination.

Fabrication of PC boards:

Printed circuit board schematics and layouts were drawn by freely available software downloaded from ExpressPCB© (http://www.expresspcb.com). After board layout was completed, layout files were submitted to ExpressPCB© for fabrication.

Schematic and layout files for the boards are available from the authors or from the NIDCD/Neuroprosthesis/QPR web site.

Strong suggestions for changes in module layout/design Board layout modifications:

- The holes for the address jumpers should be enlarged slightly so it is possible to install jumper headers into them.
- A third hole should be drilled at the stimulator header (#1) so that a different type of connector can be used (the two-conductor header was not "solid" enough).
- Holes for the monopolar/bipolar jumpers should be repositioned and possibly enlarged so that jumper headers can be installed there.
- The layout of the digital control port should be changed so that D0 – D7 are contiguous and ordered.

Design modifications:

- Address decoding logic should be changed and latches added so that four modules can be addressed using only one digital port. This would improve usability by requiring one less digital port and by making cabling easier.

Work Planned for the Next Quarter

1) We will begin experiments looking at channel interaction using electrical stimulation. We will attempt to correlate the spread of excitation as defined by spatial tuning curves in the IC with the spread of excitation as defined by reduction of EABR amplitude using inter-pulse intervals between 4 and 50 ms.

2) We will begin experiments employing implants with closer contact spacing between contacts. Our current implant uses a minimum spacing of 500 µm between contacts. In the next quarter we will fabricate an implant in which at least some contacts have a minimum spacing of 250 µm.

3) Work will continue on the acoustic model of channel interaction. We will quantify the spread of stimulus inhibition using a non-overlapping two-tone (forward masking) paradigm. We will define the time course of the inhibition by varying the gap between the end of the first tone and the beginning of the second tone. We will define the development of the interaction by varying the duration of the first tone. Finally, we will estimate the relative magnitude of the interaction by varying the intensity of the second tone.

4) Experiments will be continued to look at the effects of implant contact configuration on single channel and multi-channel stimulation. We will examine the spread of excitation using tripolar as well as bipolar and monopolar configurations.

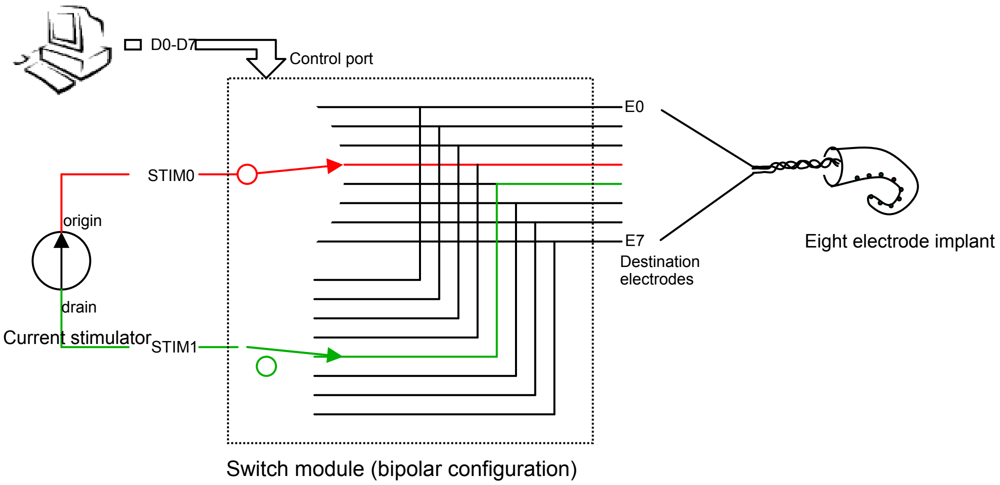
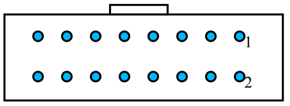


Figure 1. Use of switch module configured in bipolar mode.

Pin - sig
1 - E0
2 - nc
3 - E1
4 - nc
5 - E2
6 - nc
7 - E3
8 - nc
9 - E4
10 - nc
11 - E5
12 - nc
13 - E6
14 - nc
15 - E7
16 - nc

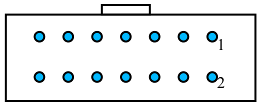
Implant connector (header #2)



(Looking into the header socket on the board)

Pin - sig
1 - GND
2 - GND
3 - D3
4 - D2
5 - D1
6 - D0
7 - +5V
8 - +5V
9 - D7
10 - D6
11 - D5
12 - D4
13 - GND
14 - GND

Digital control connector (header #3)



(Looking into the header socket on the board)

Pins 1, 2, 13 & 14 are shorted together on the board
Pins 7 & 8 are shorted together on the board

Figure 2. Module implant and control ribbon cable headers.

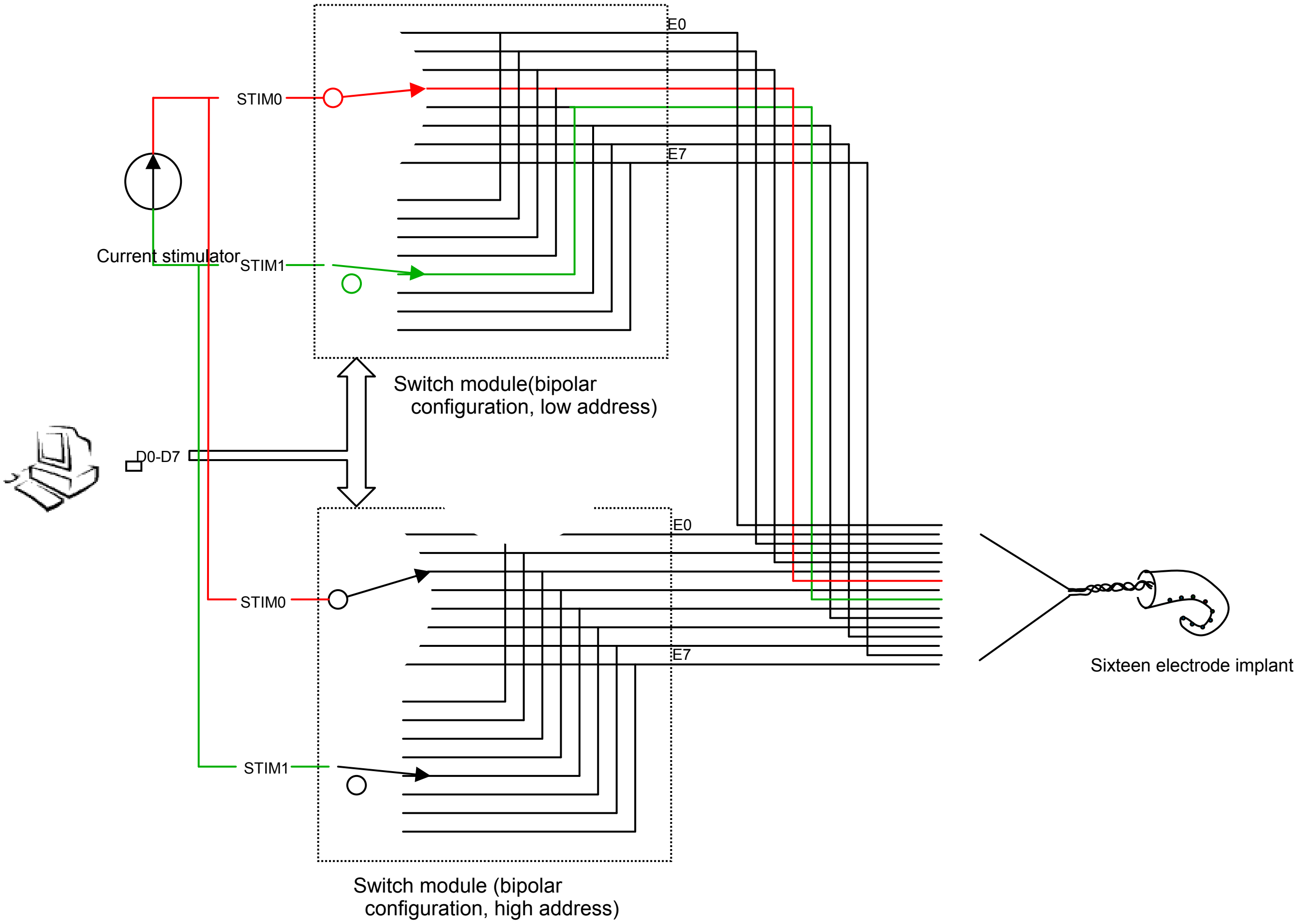


Figure 3. Use of two bipolar switch modules to stimulate a sixteen-channel implant in bipolar mode.

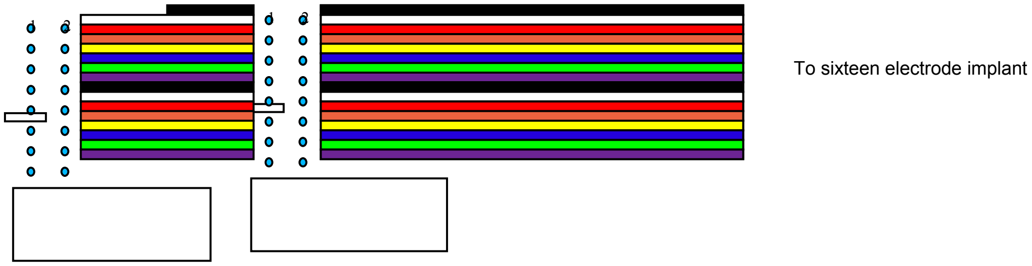


Figure 4. Ribbon cable used to connect two 8-channel bipolar modules to a 16-channel implant.

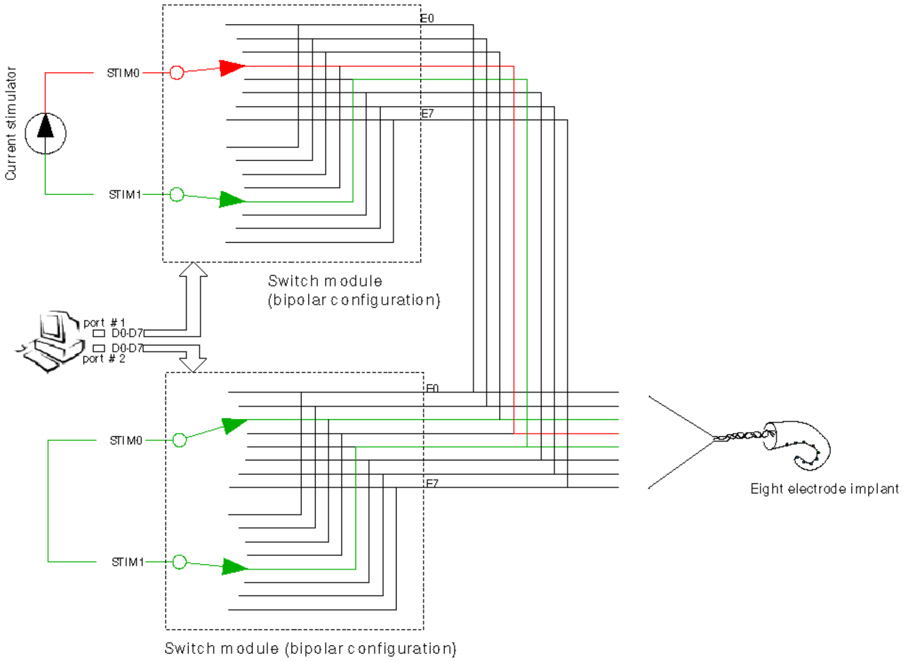


Figure 5. Use of two bipolar switch modules to stimulate in pseudotripolar (pseudoquadrupolar) mode.

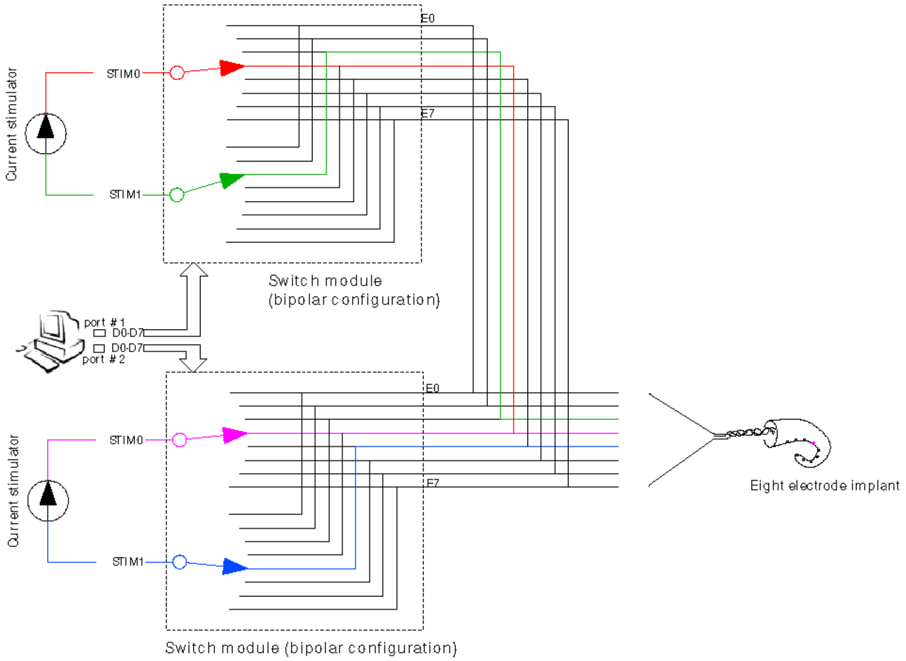


Figure 6. Use of two bipolar switch modules to stimulate in tripolar (quadrupolar) mode.

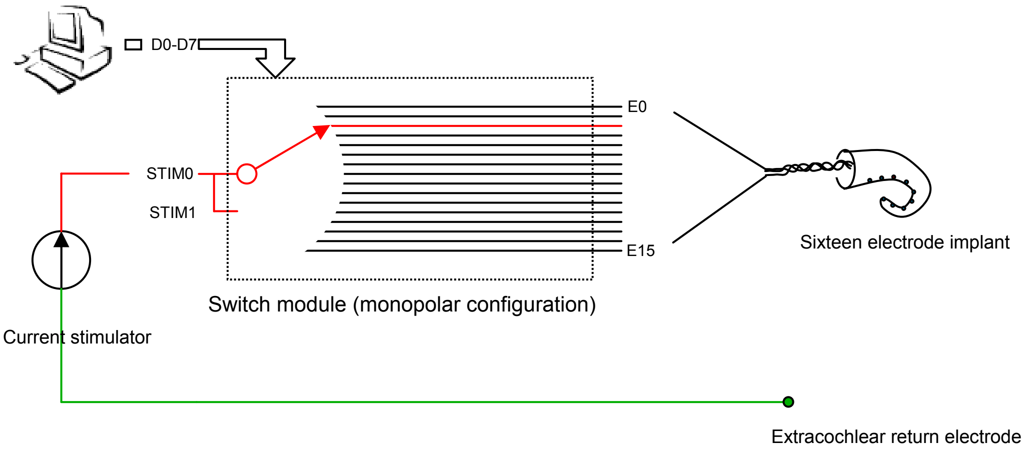


Figure 7. Use of switch module configured in monopolar mode.

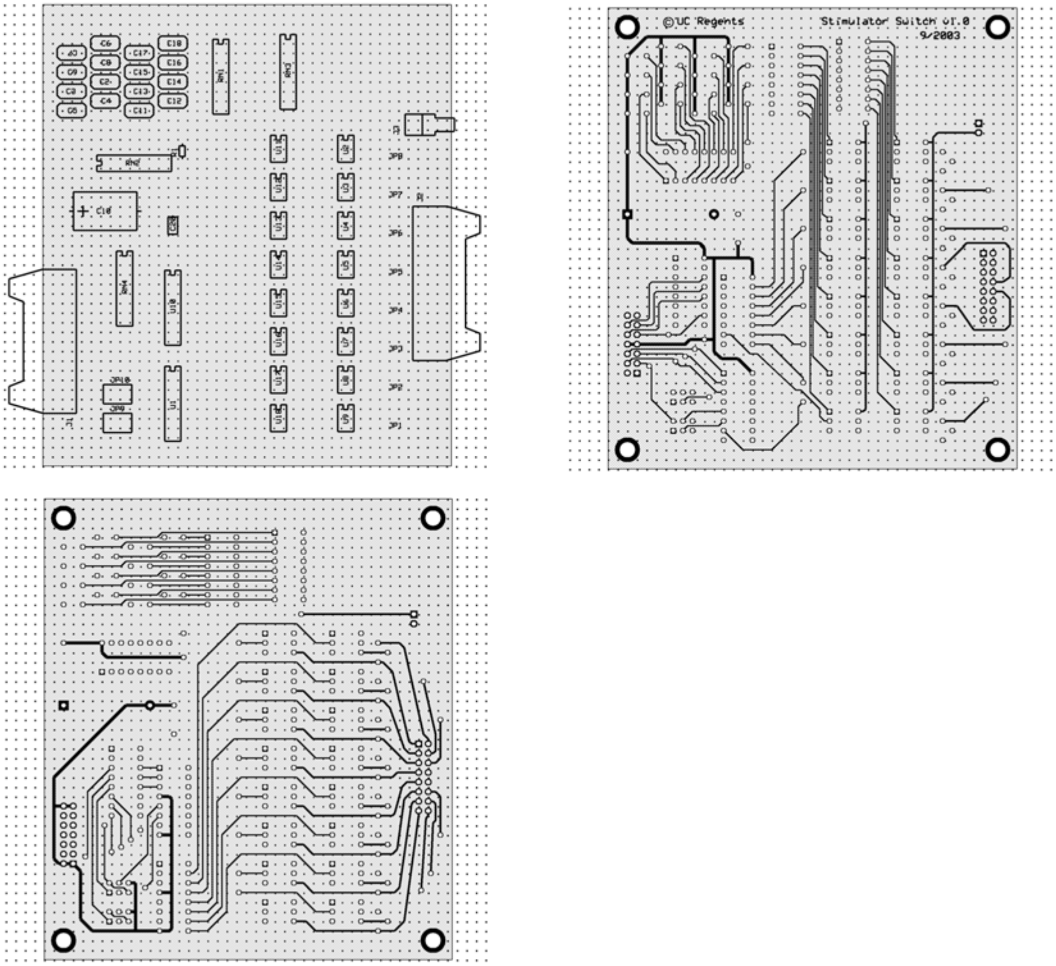


Figure 8. Switch module board copper and silkscreen.

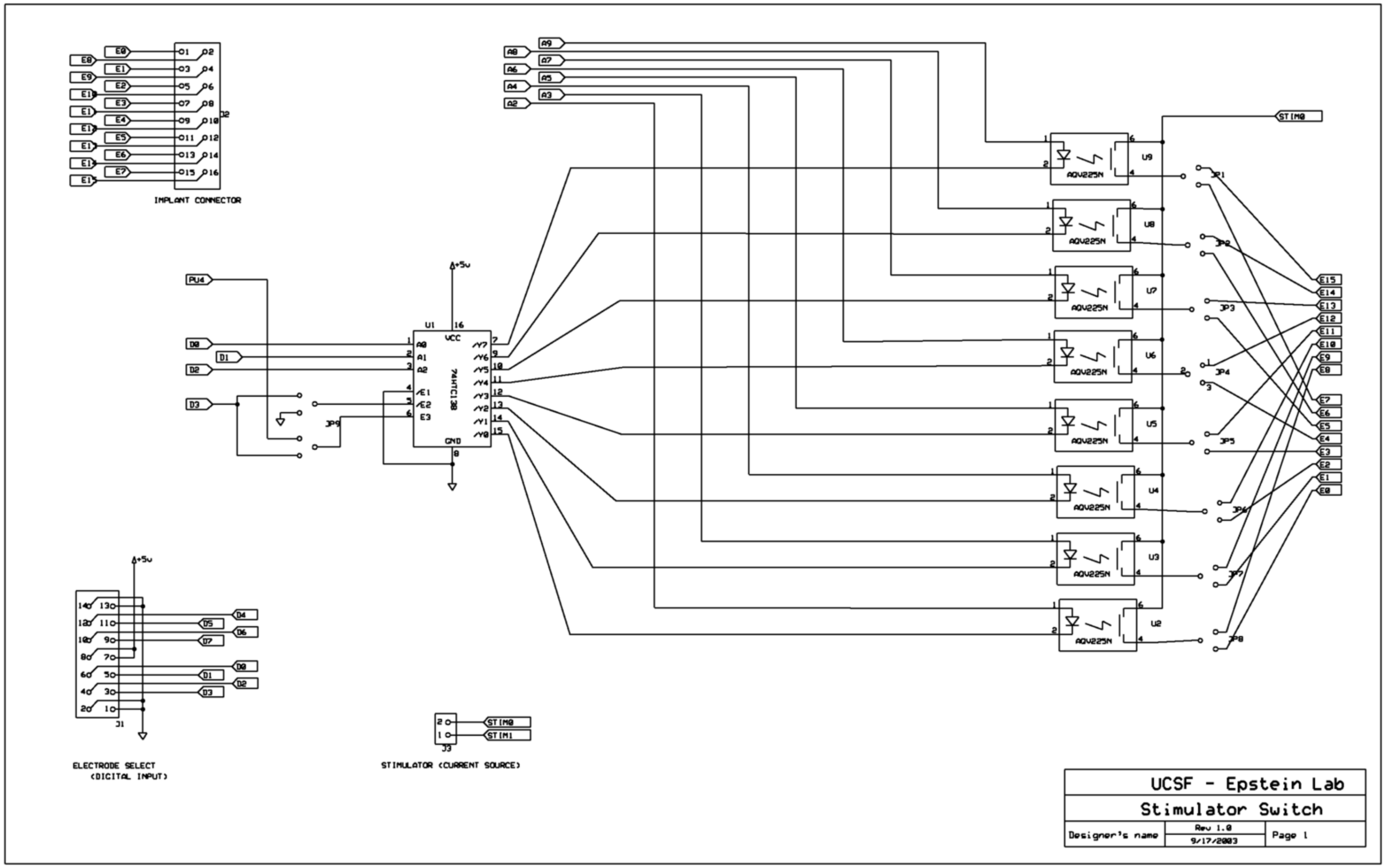


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Figure 9a. Switch module board schematic.

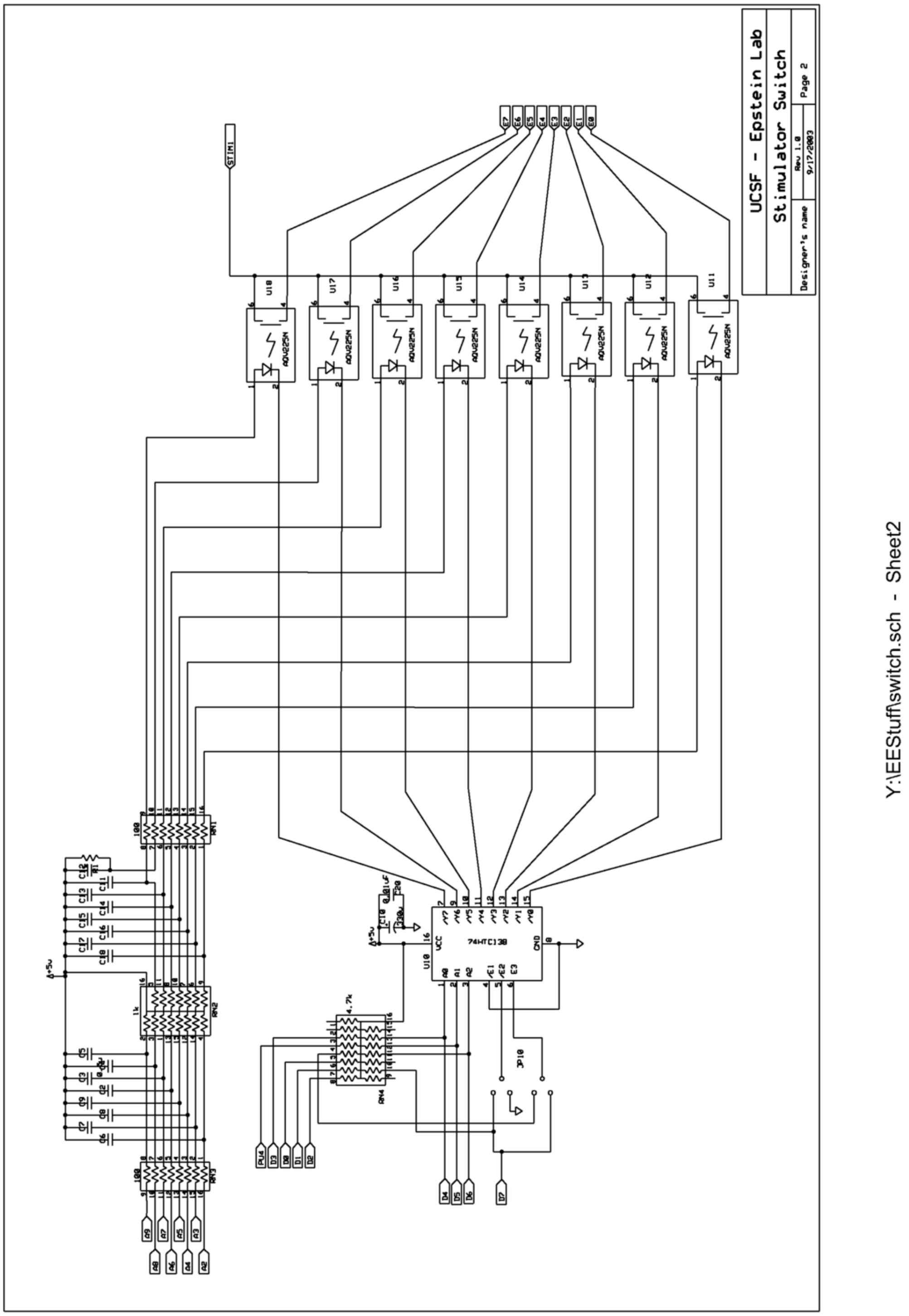

Figure 9b. Switch module board schematic (continued).