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BrainPort® Technology Tongue Interface Characterization Tactical Underwater Navigation System (TUNS)

Wicab Inc.
8476 Greenway Blvd. Suite 200
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June 2008

Interim Report for November 2006 to June 2008

Air Force Research Laboratory
Human Effectiveness Directorate
Biosciences and Protection Division
Aircrew Performance and Protection Branch
Wright-Patterson AFB OH 45433-7947

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14. ABSTRACT
Broad Agency Announcement Number 06-19 allowed for Wicab Inc. to develop a Tactical Underwater Navigation System (TUNS). The scope of this project is to develop a 1-inch square, thin module to be worn on the tongue, providing tactile information to the wearer via electrical stimulation of a high density matrix of electrodes embedded in the module. The tongue module can be programmed and used by divers (PJ's) or pilots to provide orientation cues when visibility is degraded or absent. It is less bulky than the current display technology (computers and handheld devices), reducing the burden, and allowing the warfighter more "hands free" mobility. The TUNS device has the potential to save lives in certain situations, where visibility is limited and time is of the essence.

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TABLE OF CONTENTS

LIST OF FIGURES

PREFACE

This project was funded by the Defense Advanced Research Projects Agency (DARPA) and was managed by the Air Force Research Laboratory, Aircrew Performance and Protection Branch (AFRL/RHPG) at Wright-Patterson AFB, OH. The contractor was Wicab, Inc of Middleton, WI under Contract Number FA8650-07-C-7705. The Wicab project leader was Richard Hogle. The Air Force program managers were Dr. William Albery and Lt Brad Kozenko under Work Unit Number OSMSWP12.

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1 PROJECT SUMMARY

Wicab, Inc. has developed novel technology which allows information from external devices to be sensed by humans via neuro-stimulation of the tongue. Applications are numerous and include the BrainPort® balance device to assist patients with vestibular deficits, the BrainPort vision device, a sensory augmentation device for the blind, and the BrainPort Underwater Sensory Substitution System which provides navigational cues to military divers. Current devices present data to the tongue using low density electrode arrays (100-625 elements, ~1in^2). Present and future applications may benefit from array densities and pulse timing patterns that match the spatial resolution of the tongue. Therefore, characterization of this resolution is the key to full exploitation of the tongue sensory channel.

This program represents one year's research effort to empirically measuring the electro-stimulation properties of the tongue. Advanced hardware and software were developed to support experimental protocols. Under the current program funding, to understand tongue acuity limits with respect to electro-stimulation, approximately 60 subjects and more than 200 subject hours were involved in the following experiments:

- Two-point discrimination
- Temporal gap detection
- Tongue mapping
- Spatial summation
- Contrast sensitivity

The goal of this project was to provide empirical evidence concerning the psychophysical limits of the tongue. While the results from these experiments begin to characterize the information channel, they do not represent the true limits of the channel. In order to assess the absolute limit, four experimental components need to be optimized: subjects, training, application, and technology.

Our results, with ~15 subjects per experiment, demonstrate that there is individual variation in task performance. Our participants were not chosen for their tongue perception ability, so our results may miss "super-performers" which would improve the threshold limit. In addition, subjects did not receive extensive practice with the stimuli, and thus practice could push the psychophysical limits. Second, we found that the task demands affects the reported threshold. For example, two point discrimination was ~0.75mm but spatial gratings threshold was closer to ~0.5mm. Therefore, to define the absolute threshold, either the task needs to be fixed to a task of interest or there needs to be converging evidence from a variety of experiments testing similar skills. Finally, subject performance is only as precise as the equipment being used.

To report a definite threshold we need to have hardware that exceeds performance in order to narrow in on the exact limit. In conclusion, while the suite of studies provides empirical data regarding the psychophysical characteristics of the tongue, they should not be interpreted as the absolute limits.

1.1 Significance

- **Electro-tactile psychophysical characteristics of the tongue**
  Two Point Spatial Discrimination is on average 0.75mm, with some individuals able to detect 0.25mm or better. This implies that arrays on the order of 0.125mm center-center electrode spacing (or better) may be useful for high performing individuals.

  Temporal Discrimination is on average 75ms, with some individuals performing at 50ms or better gap detection. This implies that array frame rates of 20 Hz or faster should be useful for high performing individuals.

  Test data suggests that tongue sensitivity is a function of stimulation location as well as number of stimulating tactors. In addition, the dynamic range in voltage (stimulation intensity) is a function of the number of stimulating tactors. This data may have implications on the electro-mechanical design of high density arrays, as well as the stimulation waveform and power requirements.

  Preliminary data from static 2-D grating tests indicates that average spatial discrimination is 0.6mm (compared to 0.75mm for 2pt tests). This implies that there may be strategies to further improve the average spatial discrimination ability and is the subject of continuing effort.

  Spatial acuity and temporal acuity appear to differ within individuals - high performers in one modality are not necessarily high performers in another. This presents opportunities to train individuals whose physiology allows peak performance across modalities, to tailor information to individual performance, and to tailor arrays for specific applications.

  Finally, data from this study confirms that electro-neurostimulation of tongue is on par with other stimulation modalities: mechanical grating ~0.500mm (Van Boven, 1994) and vibro-tactile at ~20Hz (Ezawa, 1988).

- **High Density Array Design and Experiment Control**
  Experimental data indicates 0.125mm electrode spacing (200/inch) should match the tongue's spatial acuity. Using a simple fabrication technique, arrays with 0.152mm spacing were assembled (densities beyond this level requires a significant technology investment). These near-optimal arrays allow advanced testing of dynamic information on the tongue.

  An electrical control system was designed and implemented which allows concurrent control of all electrodes in an array. This system manages the safe delivery of stimulation to any number of simultaneous electrodes, as well as manipulation of the return path geometry. In addition, stimulation waveform patterns can be defined for evaluation of waveform on spatial and temporal detection properties. The system is designed to manage up to 27,000 electrodes, although for practical testing, we have limited the current implementation to 2000 element arrays.

An experimental control software application was developed to allow researchers to define experiments using any configuration of electrode geometry and stimulation waveform patterns. Experiment sessions are defined and executed to present stimulus information to subjects and record their responses. All data is archived for off-line analysis.

All human subject testing was done under an IRB approved protocol.

Results of experiments and analysis of data are presented below, followed by a summary of significant hardware and software development.

2 STUDIES AND RESULTS

2.1 Two-Point Discrimination

Two-point discrimination was performed using a modified BrainPort Balance Device C200 (BBD-C200). Nine linear arrays with ten electrodes each were produced with industry standard printed wiring board technology. The individual electrodes ranged in diameter from 1.5mm to 0.169mm and were spaced (center to center) at a distance of 1.5 times the electrode diameter. The smallest electrode size and spacing represents the highest resolution readily available from commercial printed wiring board vendors. Sufficient arrays were produced so that each test subject used a new array, minimizing the effects of electrode corrosion and resultant changes in impedance.

The stimulus generation circuit employed in the BBD-C200 consists of a ColdFire 32-bit microcontroller, Texas Instruments digital to analog converter (TLV5630), Burr-Brown operational amplifier (OPA4132), and a bank of Analog Devices demultiplexers (ADG408BRU) used for routing the stimulus signal to any one of one hundred electrode addresses. Each output of the demultiplexers are connected to an AC coupling capacitor (0.1μF ceramic) with the opposite side of that capacitor connected to the tongue placed electrode.

Internal pilot studies suggested that some subjects could discriminate two stimuli spaced 0.5mm apart. As a result, we selected a linear electrode array with 10 electrodes, each 169 micrometers (μ) diameter and spaced 254μ apart (center to center) for the formal two point discrimination experiment. This array enabled conditions that could both exceed performance and also be within the range of successful performance. Each active electrode presented a continuously repeating stimulation waveform. The waveform scheme consisted of six double stimulating pulses (21.4μsec each separated by 5μsec) repeating at 369Hz. After every 6 pulses, 2 pulses were presented at 0V (total period of waveform was 21.68ms). When two tactors were presented, the first tactor fired 51.6μsec after the second tactor. Pulse amplitude was fixed per subject. Each subject set their own comfortable working amplitude up to 24.5V prior to the experiment, providing comfortable stimulation. This waveform scheme was selected because sensation was perceived as a comfortable and continuous stimulation.

Sixteen subjects (10 men; 6 women) participated, ranging in age from 18-39 years (mean 24.5yrs). Experiment duration was approximately two hours. Subjects were recruited from the Madison, WI area. All subjects gave informed consent with a study protocol approved by the New England IRB. Pulse amplitude (in volts) was determined individually before running the two point discrimination experiment. Subjects were presented with trials containing one or two tactors firing on an array. They were instructed to manipulate a hand held slider control, allowing each subject to explore and adjust the stimulation to a comfortable working level. Once a comfortable level was reached, subjects indicated their response by pressing a button on the hand-held control. "Working level" was defined as a stimulation level that was strong and comfortable for at least five seconds. Intensity values (voltage) were gathered for one and two contiguous firing tactors. Each measurement was repeated several times across multiple tactor locations. For each subject, the mean "working level" for one and two contiguous points was used as the fixed voltage intensity for the two point discrimination test. These values ranged from 18-25V across participants (mean 21.46V).

Trials were presented in five experimental runs, blocked by the separation between two tactors. These conditions were: 0.254mm (no gap), 0.580mm (1 tactor gap), 0.762mm (2 tactor gap), 1.016mm (3 tactor gap) and 1.261mm (4 tactor gap). In each block, half of the trials contained only one stimulating tactor, while the other half contained two firing tactors of the fixed condition distance. The order of the five experimental blocks was pseudo-randomized for each subject.

Subjects were instructed to press one button on the hand-held control if they felt one stimulus on their tongue and a different button if they felt two stimuli on their tongue. They were encouraged to use the tip of their tongue (or any other part of the tongue) to search for and/or to explore the stimulation in order to respond maximally. There was no response time limit. In this way, subjects could explore the stimulus with whatever part of the tongue they felt gave them the best information.

To familiarize subjects with electrotactile stimulation and the procedures, subjects were given 5-10 minutes of interactive practice trials. Participants sampled a few trials of each of the conditions, becoming acquainted with the trial types. During this practice phase, the researcher labeled the conditions as being truly two points or one. Subjects were told there may be trials where they may not be able to confidently give a correct response. They were reassured that this was necessary in order to get to the limit of spatial resolution on the tongue. During experimental testing, performance feedback was not provided.

The primary endpoint will be a threshold defined by a group d-prime greater than or equal to one (by subject and by group), indicating subjects are sensitive to the presence of two categories (CBASEE 1985). Calculating d-prime (d'), a measure of sensitivity in a discrimination task, is computed by the standardized difference between the false alarm rate and the hit rate: $d' = z(H) - z(FA)$ (Macmillan & Creelman 2005). The hit rate is the proportion of correctly identified trials of two points, when two points were actually stimulated. The false alarm rate is the proportion of incorrect trials where the subject reported two points, but only one point was actually stimulated. The numeric output of d-prime represents the perceived distance between the two categories. A d-prime near zero represents chance discrimination,

where subjects are insensitive to the condition categories. When d-prime is greater than one, at least one standard deviation separates the two response categories indicating that subjects are sensitive to and correctly responding to the condition categories.

As a secondary endpoint, individual d-prime measures by condition were statistically explored post-hoc using a one way ANOVA. Individual differences were further explored by computing the percentage of subjects whose individual performance exceeded d-prime discrimination greater than one.

Figure 1 illustrates performance across participants. The line graph (left y-axis) represents the group's mean d-prime performance across the five tactor spacing conditions. As a group, performance exceeded d-prime>1 when tactors were spaced 0.762mm (2 tactor gap). A one way ANOVA revealed a significant main effect for tactor spacing ($F(4,60)=4.466$, $p<.005$). As the tactor spacing increased, performance improved. The line graph (right axis) illustrates the percentage of subjects in each condition who individually exceeded threshold. For example, 12.5% of subjects scored above threshold in the most closely spaced 254μ condition. So while the group average threshold is 0.762mm, there are individuals who have better than average discrimination abilities. This may suggest that an individual's actual limit may be better than 0.254mm spacing.

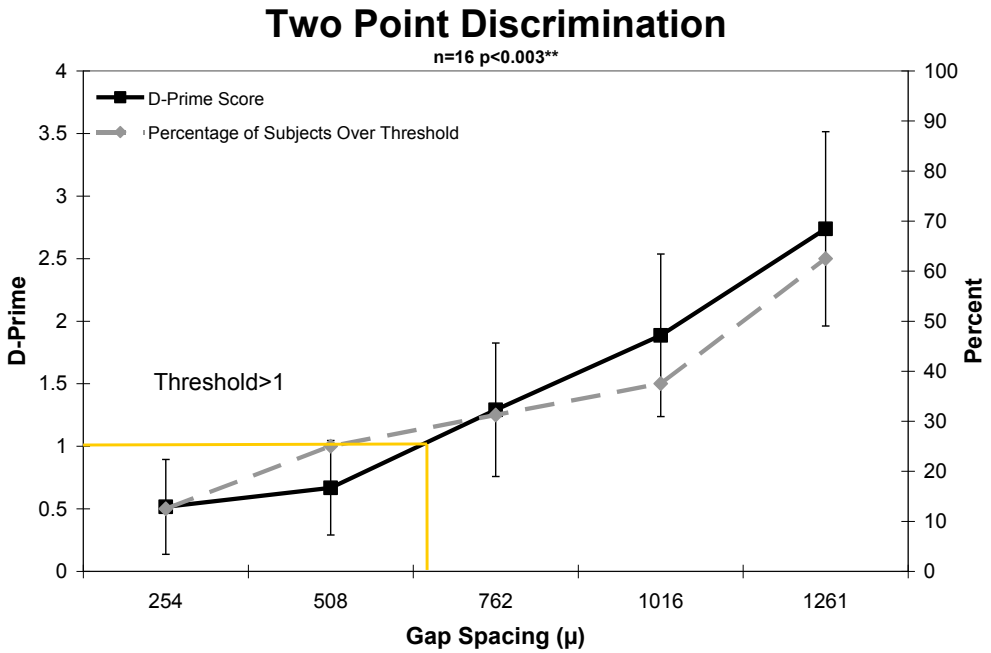


Figure 1. Two Point Discrimination Across Participants

2.2 Temporal Gap Discrimination

Gap discrimination was performed using a modified BrainPort Balance Device C200 (BBD-C200) as described above. Internal pilot studies suggested temporal gaps with the smallest

array (0.254mm spacing) were difficult to discriminate. Using a linear array with 10 tactors sized 0.667mm spaced 1.0mm apart, internal subjects were able to feel temporal gaps of 50-100ms in duration. With this array, conditions were generated that could both exceed performance and also be within the range of successful performance. All gap discrimination conditions use a continuous repeating pulse scheme presenting 1 pulse for 25μs wide every 125μs (frame) to each tactor with a programmable "gap" of no stimulation on one of the tactors. For the "gap" condition, the tactor pulses for a total of 500ms (four frames) followed by an "off gap" of 33-250ms.

Sixteen subjects (10 men; 6 women) participated, ranging in age from 18-39 years (mean 24.5yrs). Experiment duration was approximately two hours. Subjects were recruited from the Madison, WI area. All subjects gave informed consent with a study protocol approved by the New England IRB. Some, but not all, subjects participated in the 2-pt Discrimination Test. Pulse amplitude (in volts) was determined individually before running the gap discrimination experiment. Subjects were presented with trials containing tactors firing on the array with variable gaps in the continuous stimulation. They were instructed to manipulate a hand held slider control, allowing each subject to explore and adjust the stimulation to a comfortable working level. Once a comfortable level was reached, subjects indicated their response, using either a thumb or finger to press a button on the hand-held control. "Working level" was defined as a stimulation level that was strong and comfortable for at least five seconds. Intensity values (voltage) were repeated several times and averaged across conditions, creating a mean "working level" as the fixed voltage intensity for the gap discrimination test.

This experiment consisted of five blocks of experimental runs containing twenty Two-Alternative Forced Choice (2AFC) trials for a total of 100 trials. Each trial contained two stimulating tactors, one on the right and one on the left, spaced four tactors apart. For every trial, one tactor was continuously firing (as defined above), while the other tactor had a temporal gap. The targeted gap stimulus was presented "on" for 500ms followed by one of five "off" gaps: 33ms, 50ms, 75ms, 100ms and 250ms. This target stimulus cycled through "on" and "off" continuously while the other tactor presented a continuous waveform. The two stimuli were presented until the participant indicated which stimulating tactor had the temporal gap.

Subjects were instructed to press the left button if they felt the stimulus had a temporal gap on the left, else, press the right button if they felt it on the right. Half the correct responses for the trials for each were presented on the right and left respectively. Again, the participant was allowed to take as much time as needed and a free moving tongue was allowed. In this way, subjects could explore the stimulus with whatever part of the tongue they felt gave them the best information. The order of the five blocks was pseudo-randomized for each subject and there was no performance feedback given. Two point discrimination performances translated into a percent correct score for each temporal gap and subject. Effective discrimination threshold was defined as when the percent correct was greater than 75%.

Figure 2 illustrates performance across participants. The line graph (left y-axis) represents the group's mean d-prime performance across the five temporal gap conditions. As a group, performance exceeded d-prime>1 when tactors had a gap of at least 75ms. A one way ANOVA revealed a significant main effect for tactor spacing ($F(4,60)=6.239$, $p<.005$). As the temporal gap increased, performance improved. The dotted line illustrates the percentage of subjects in each condition who individually exceeded threshold. While the group average threshold is 75ms for gap detection, there are individuals who have better than average discrimination abilities. This may suggest that an individual's actual limit may be better than 50ms.

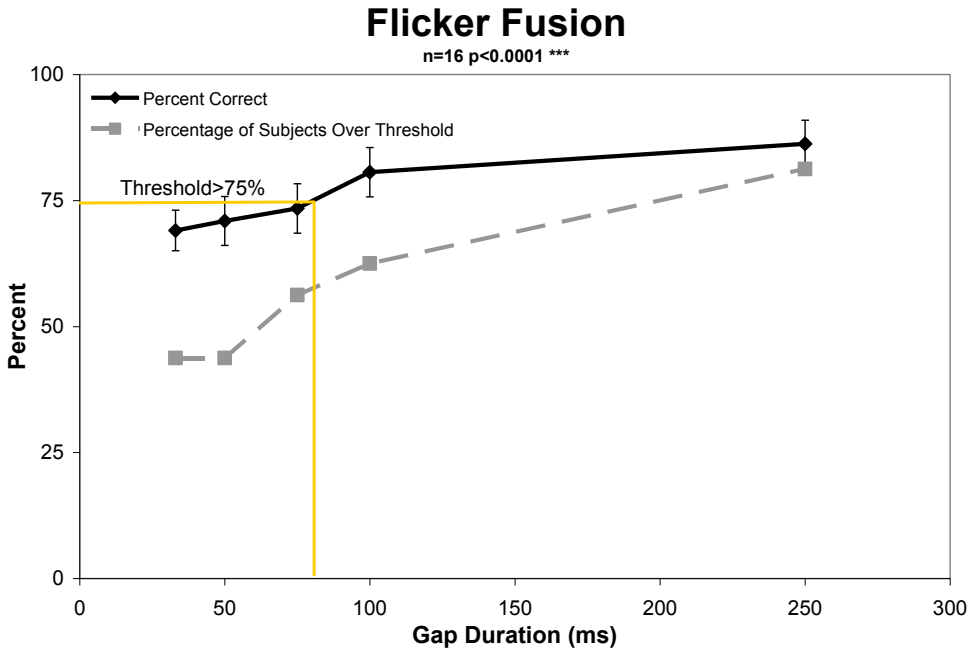


Figure 2. Gap Detection Across Participants

2.3 Tongue Mapping & Spatial Summation

A review and analysis of the tongue mapping and spatial summation data using the 25x25 tongue array suggests tongue sensitivity is a function of stimulation location as well as number of stimulating tactors. A representative three-dimensional tongue sensitivity map is included (*Figure 3*). The front center of the tongue has the greatest sensitivity, as indicated by the lowest voltage region. As stimulation is placed near the back of the tongue, the mean sensitivity is decreased. When many tactors are stimulated, less voltage is required for threshold and working levels. When one tactor is stimulated, more voltage is required for threshold and working levels. The spatial summation graph, Figure 4, illustrates that sensitivity is a function of the size of the stimulating area on the tongue. In addition, the graph illustrates the dynamic range in voltage as a function of the number of stimulating tactors, where there is a greater range when one tactor is firing as compared to a smaller range when nine tactors are firing.

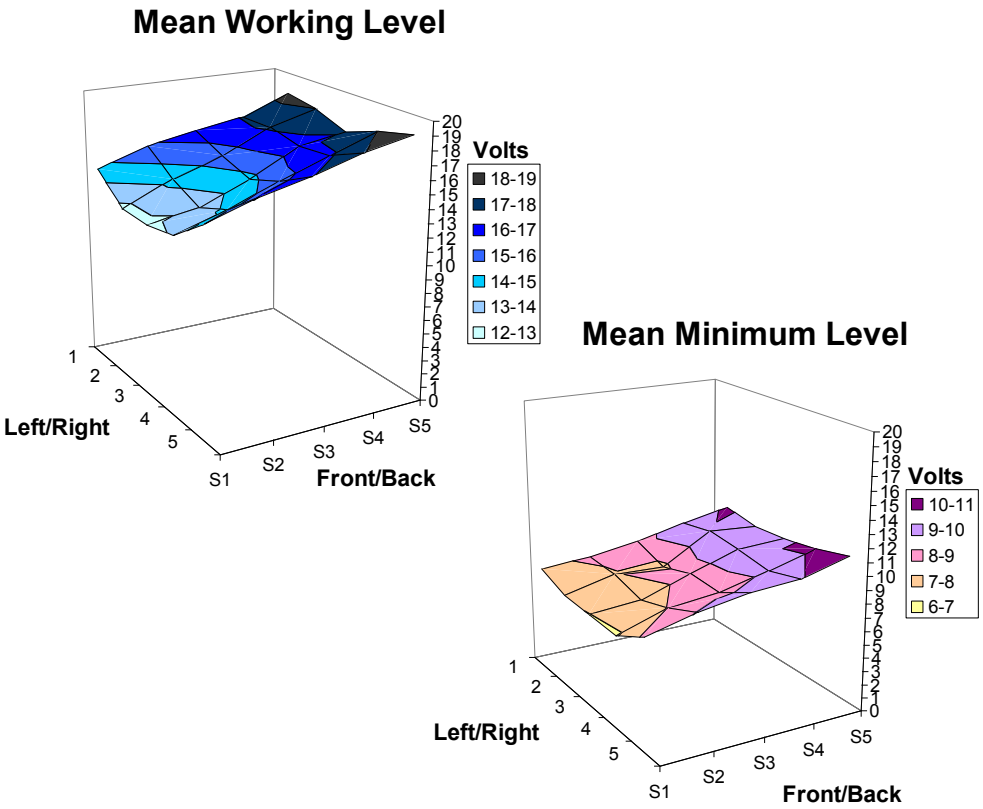


Figure 3. Tongue Sensitivity Maps

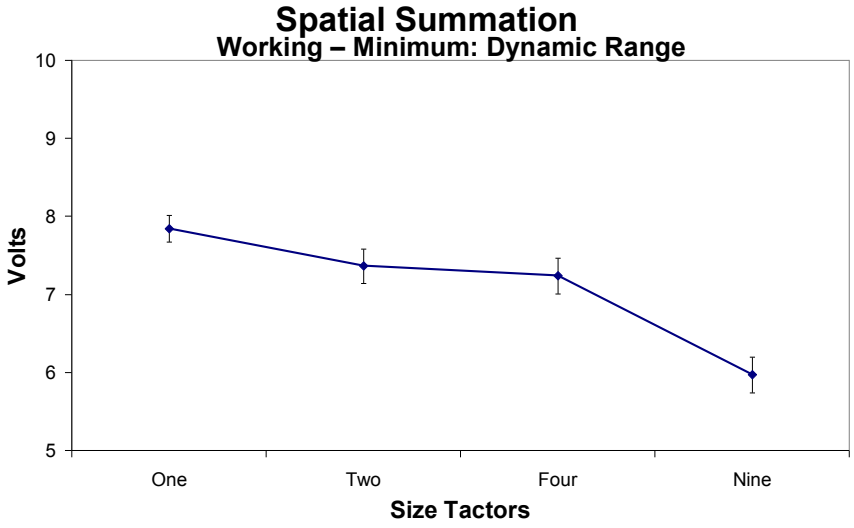


Figure 4. Spatial Summation

2.4 Contrast Sensitivity

Using the 20x20 portion of the High Density TUNS array (76µm diameter tactor, 152µm center-to-center spacing), contrast sensitivity was measured in five participants. Twenty-five experimental blocks included five trials each of five spatial line gratings presented at five different contrast levels:

5-gap (760µm)	100% Working Level Voltage
4-gap (608µm)	80% Working Level Voltage
3-gap (456µm)	60% Working Level Voltage
2-gap (304µm)	40% Working Level Voltage
1-gap (152µm)	20% Working Level Voltage

Figure 5 illustrates the general experimental design (not to scale). Each experimental block consists of 15 randomly presented grating orientations: 5 horizontal, 5 vertical or 5 neither (diagonal). Participants were required to make a Three-Alternative Forced Choice indicating the direction of the presented grating. Perceptual threshold is reached in conditions where percent correct exceeds 66.67%.

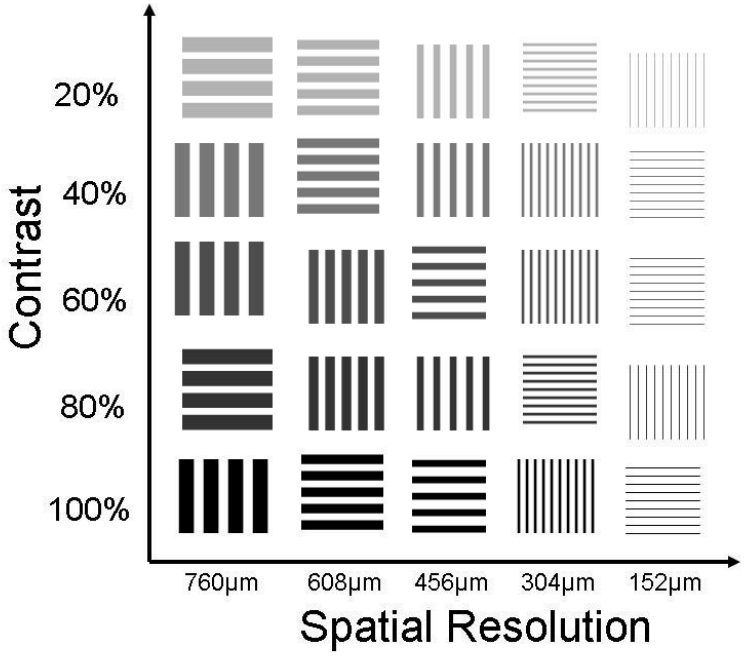


Figure 5. Contrast Sensitivity Experiment Design

A two-way ANOVA (gap-spacing x contrast) was performed, resulting in a significant main effect of gap spacing, Figure 6, ($F(4,16)=6.044$, $p<.004$), a significant main effect of contrast level, Figure 7, ($F(4,16)=5.406$, $p<.006$), with no significant interaction.

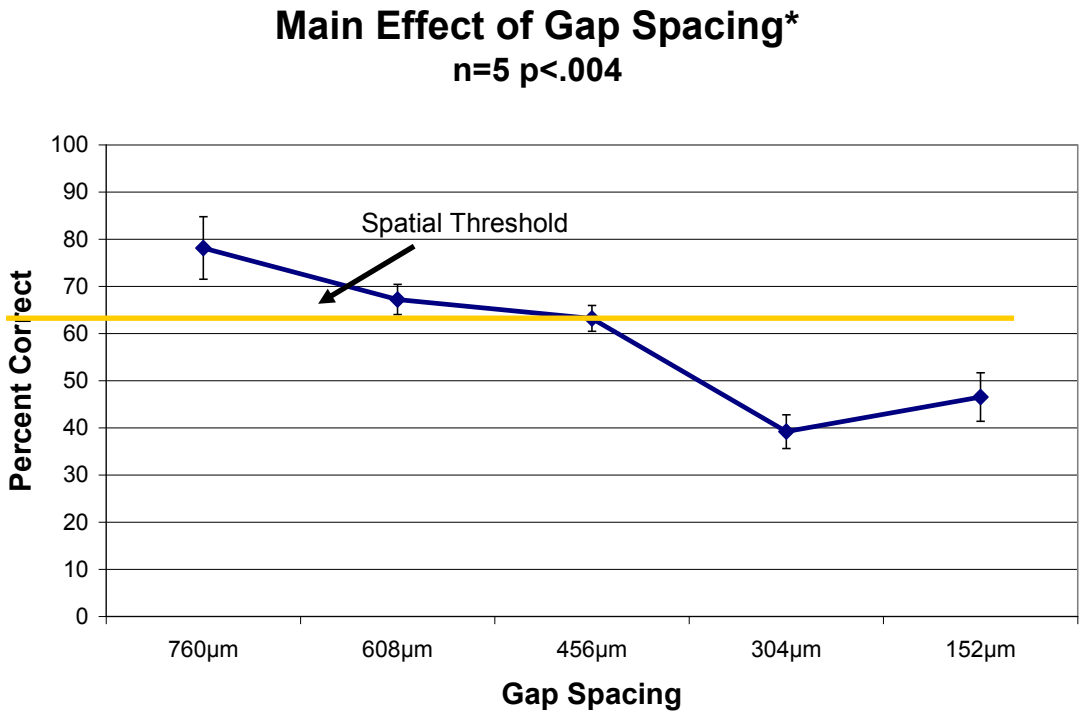


Figure 6. Main Effect - Gap Spacing

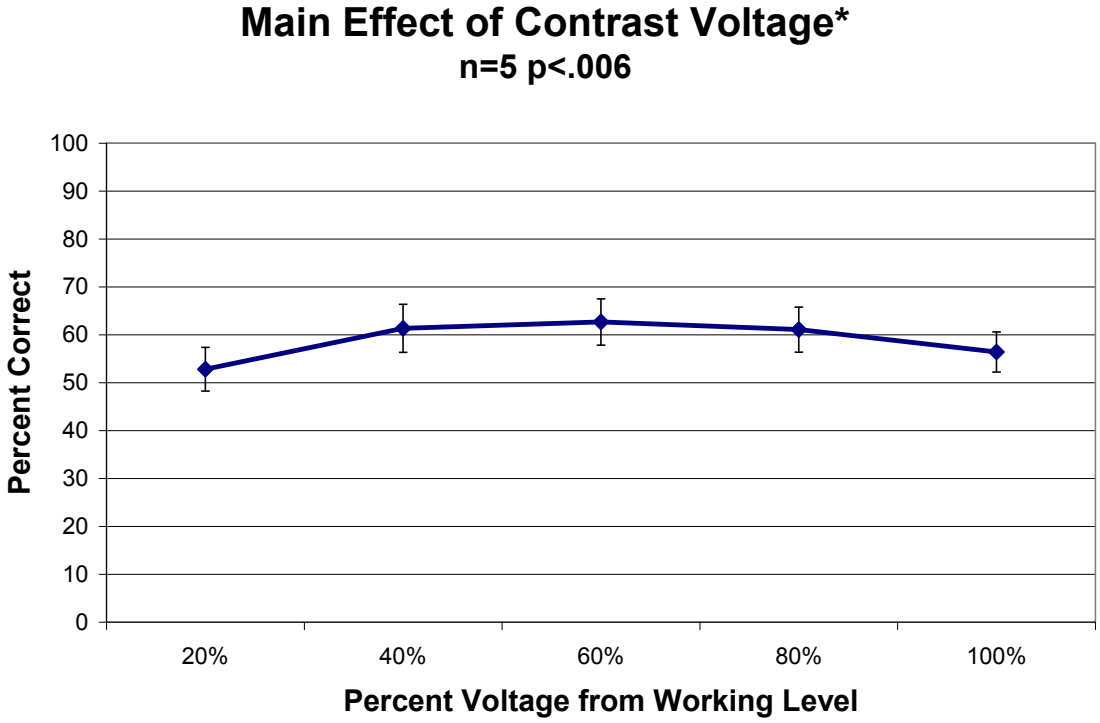


Figure 7. Main Effect - Contrast Voltage

Group percent correct values for each experimental condition are shown in the following table (Table 1). Conditions that meet exceed threshold are highlighted in yellow.

Table 1. Percent Correct for Contrast Experimental Conditions

	760µm	608µm	456µm	304µm	152µm
20%	74.67	57.33	54.67	37.33	40
40%	84	74.67	57.33	37.33	53.33
60%	84	64	68	38.67	58.67
80%	82.67	72	66.67	40	44
100%	65.33	68	69.33	42.67	36.67

Using this data, a graphical "Contrast Sensitivity" chart is included, Figure 8, (not to scale), with conditions that meet or exceed threshold are highlighted in yellow. Two conditions, colored in light green (100%/760um, 60%,608um), are close to threshold and one would assume with more subjects would be included as above threshold.

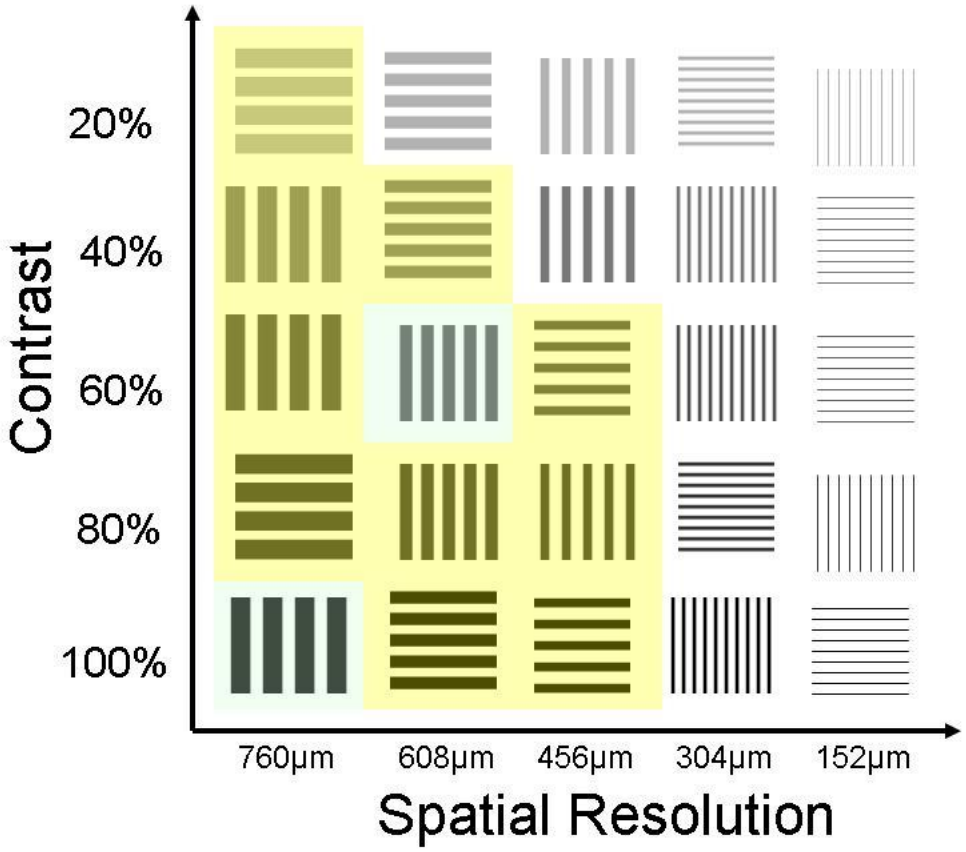


Figure 8. Contrast Sensitivity Chart

3 HARDWARE AND SOFTWARE DEVELOPMENT

Hardware development over the course of this project went from simple linear arrays for initial spatial discrimination testing to a final 20x100 High Density Array and simultaneous control system. Recent engineering effort for the this program has been focused on building the High Density (HD) Array Control System, which is now in use for discrimination testing.

The overall System Architecture is shown below, Figure 9. This system provides micro-electrode transcutaneous neuro-stimulation on a new scale: thousands of simultaneous active electrodes and up to 96 unique waveforms (limited only by memory).

The Experiment Workstation runs the experiment control software application and provides a Common Software Interface, an Ethernet Connection to Control Modules, a Socket communications protocol. It is designed to scale with the control hardware.

The HD Controller Boards are designed to manage 100 electrodes each. They include a Linux-based Microcontroller (Gumstix) executing custom control software (the Experiment Virtual Machine), an FGPA (10MHz waveform clock) providing Master-Slave synchronization across all control boards, simultaneous electrode activation, and the electrode drivers. The control boards are designed to allow each electrode to be an active electrode (stimulating), a return electrode, or floating (out of the circuit).

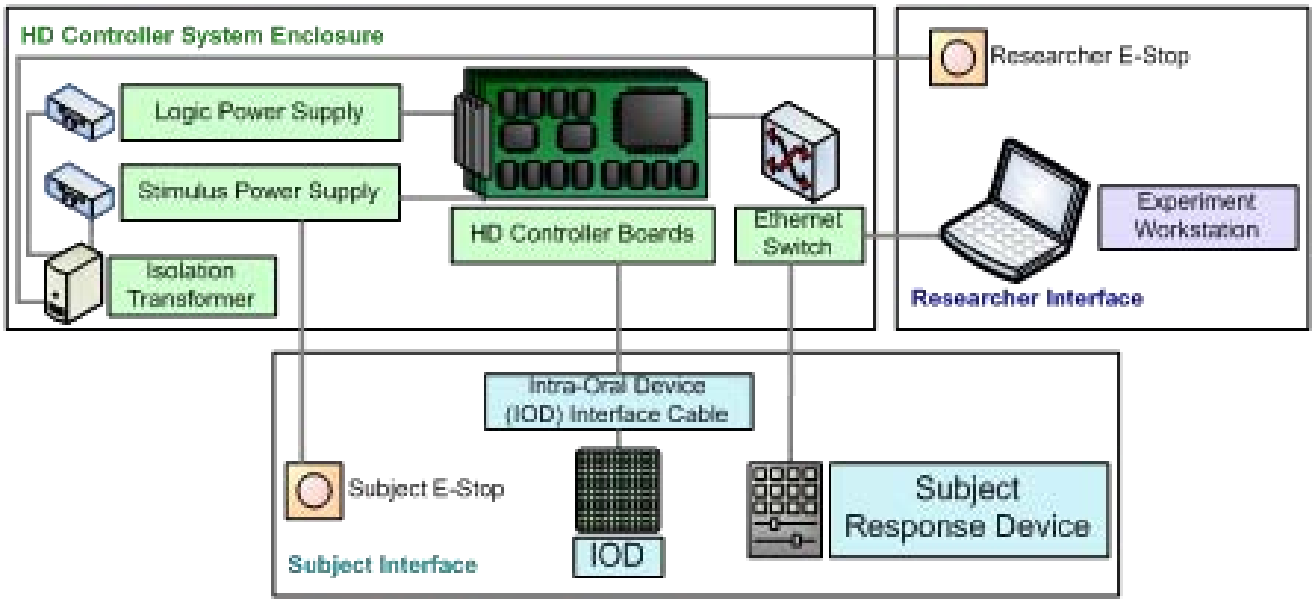


Figure 9. High Density Array Control System Architecture

Figure 10 is a block diagram of the core hardware architecture.

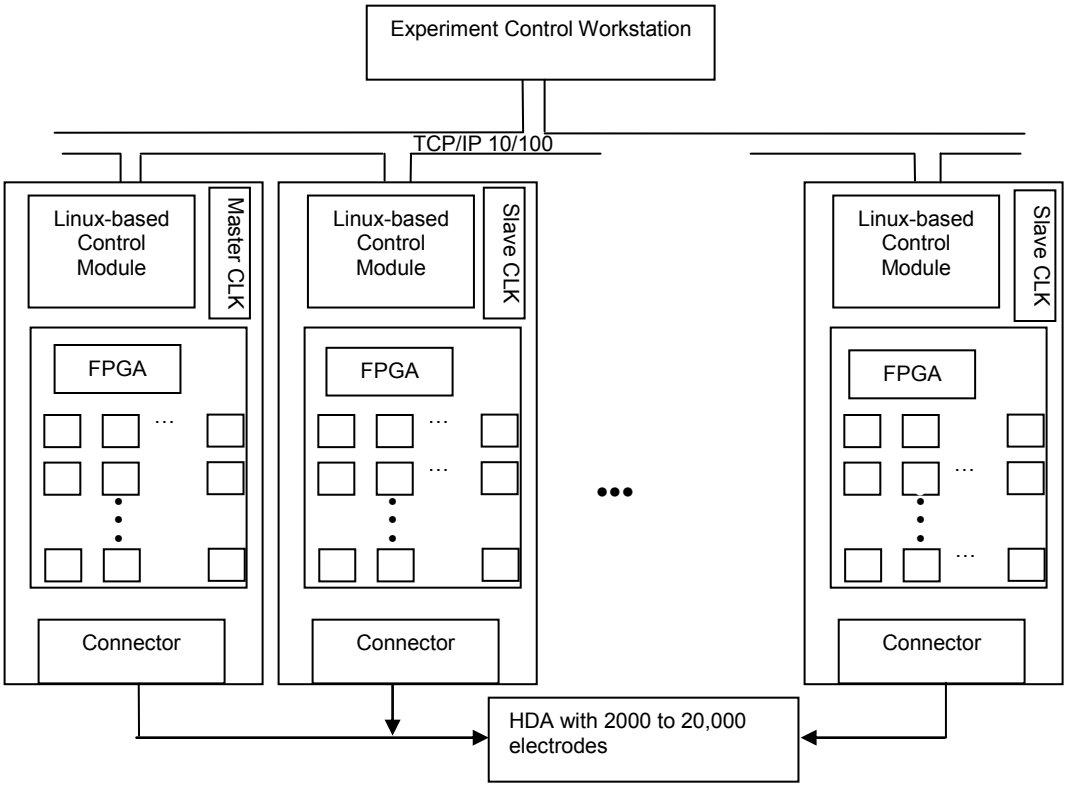


Figure 10. Core Hardware Architecture

3.1 Hardware

Significant Accomplishments: Design and manufacture of the HD Control boards. Each board manages the state of 100 electrodes and allows simultaneous activation of any or all at a given time. Figure 11 shows a completed HD Control board. We currently have 22 boards in house.

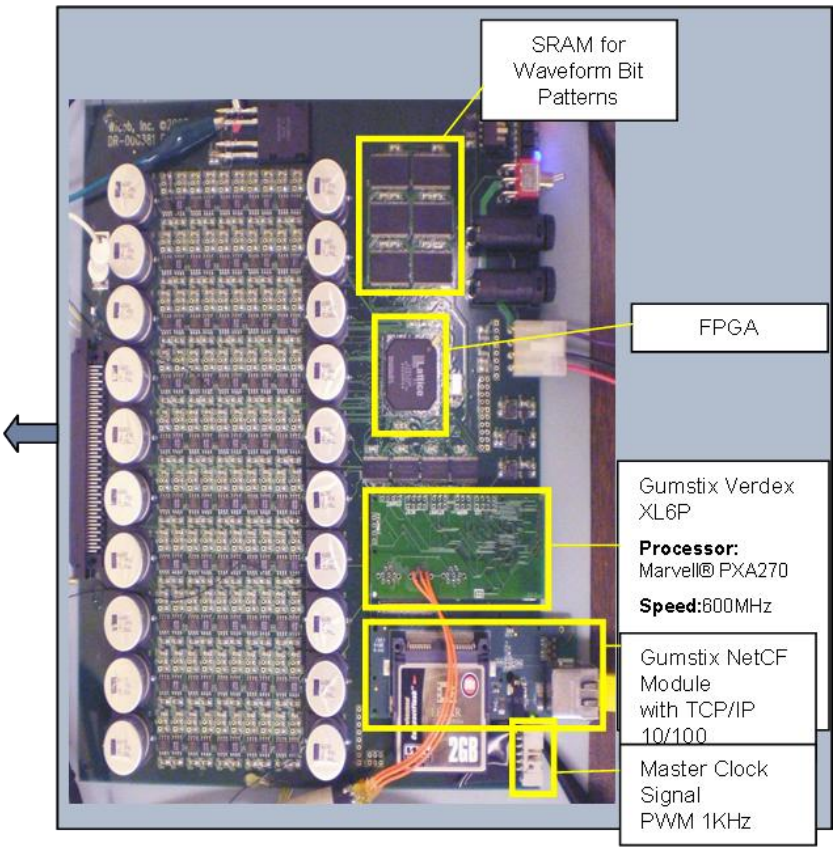


Figure 11. Complete HD Control Board

- To control the array stack-up described below, an HD Control board is required for every 100 electrodes. Figure 12 shows a board being inserted into the instrumentation rack. The initial system will handle 2000 electrodes (20 control boards). Each board has a cable connecting it to a set of electrodes (cables are seen hanging off the front of several boards).

Figure 12. Control Board Insertion

- When fully populated, the instrumentation rack, Figure 13, contains the electro-mechanical interfaces allowing the Experiment Workstation (a PC with custom software) to control each HD board and every tactor.

Figure 13. Populated Instrumentation Rack

This initial implementation was sufficient to support the planned experiments. During the course of the project, Wicab and DARPA agreed to limit testing to devices with 2000 electrodes before deciding whether fabrication of larger capacity arrays is necessary (Note that the system is designed to scale up to 20,000+ electrodes).

Wicab used this high density array system to conduct studies at the limits of spatial, temporal and contrast discrimination (Figure 14). In addition, the control architecture supports waveform shaping and simultaneous activation of many electrodes (compared to previous systems where only one electrode at a time is activated).

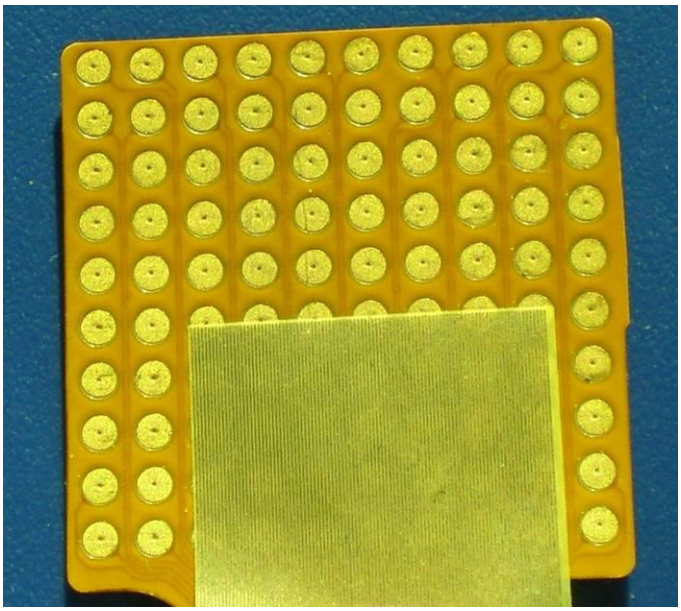
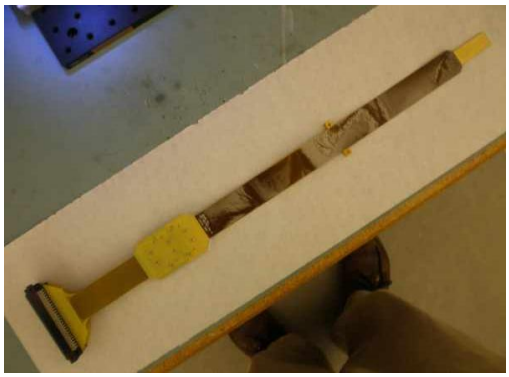


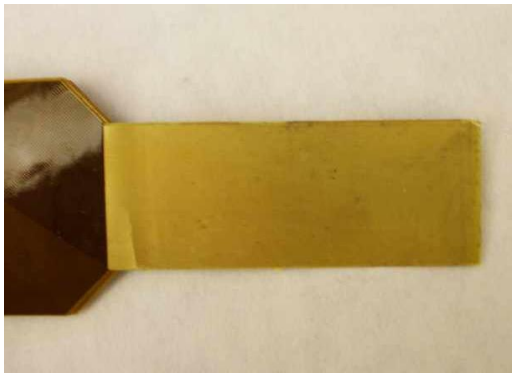
Figure 14. High Density Array – 100 Element Strip, Compared to Original 10x10 Array

High Density Array Stack-up

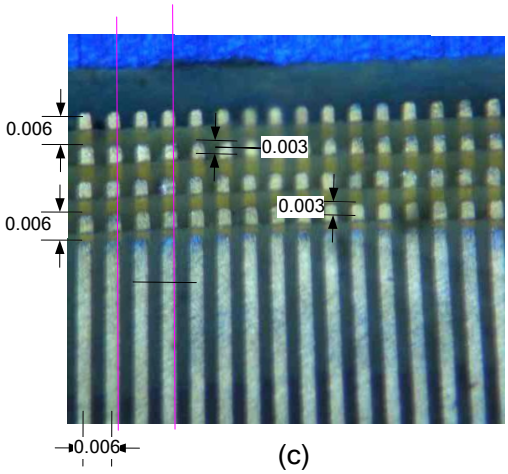
Figure 15.(a) shows the completed proof of concept prototype validating the design and fabrication approach to the assembly.



(a)



(b)



(c)

Figure 15. Strip Array Stack-up

At arms length the individual electrodes are barely visible (Figure 15.b) to the naked eye.

Figure 16 shows a single strip array, with a 20 layer stack of strips.

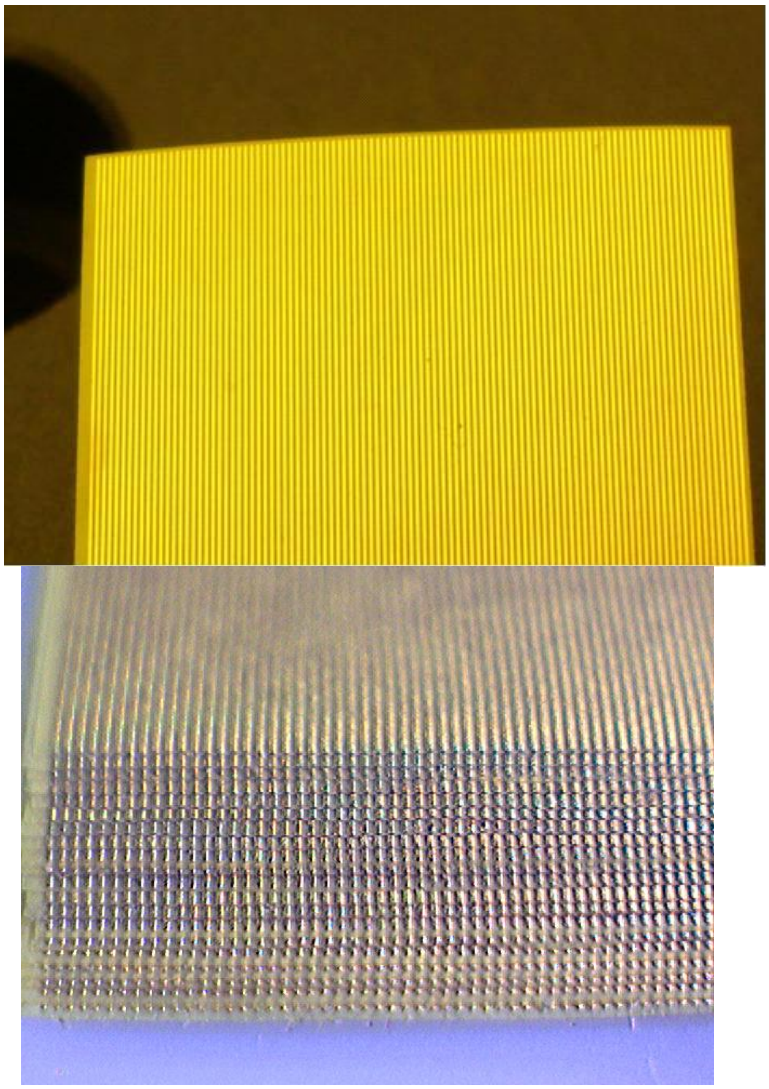


Figure 16. Stack-up and Single Strip Array

3.2 Software

Software modules have been developed for the experiment system throughout the TUNS project to support psychophysical experiments and provide the necessary mechanisms to run subjects on two tongue stimulation platforms (WG-C200 and HD Controller). Data formats were also developed to encode experiment parameters, waveform parameters/timings, stimulus patterns, etc. for use with the custom software being developed. The data formats and software modules designed during this project are summarized in this document.

3.3 Stimulation Platform

3.3.1 Virtual Machine Concept

In order to describe stimulation parameters in a generic enough format to produce similar system behavior across hardware implementations, a virtual machine design has been used. Tongue stimulation patterns/timings are parameterized using a custom instruction set that executes in the virtual machine via a scheduled run-to-completion scheme. Programs written using the instruction set are described as „Stimulus Programs' (Figure 17). A fixed master clock drives the virtual machine, synchronizing voltage outputs at the tactors. Only a few of the instructions are hardware dependent (those related to actually commanding the hardware voltage outputs and waveform selections) implying that the virtual machine can easily be ported to various hardware platforms.

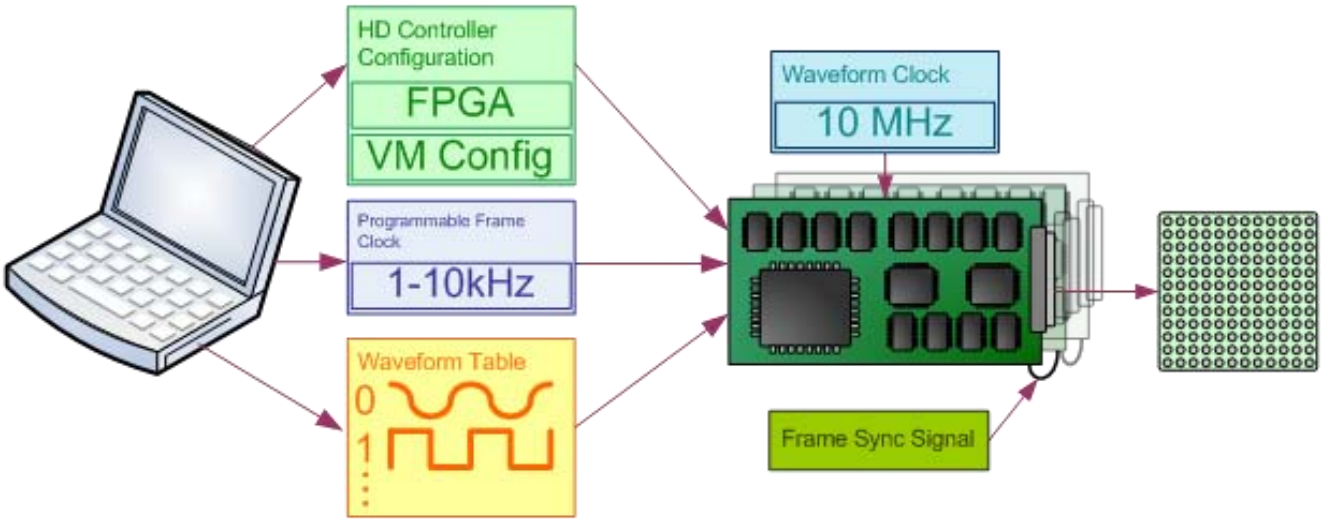


Figure 17. Stimulus Program WorkFlow

3.3.1.1 Instruction Set

The instruction set is outlined in detail in Appendix A – Virtual Machine Instruction Set. Instructions have been designed for such tasks as tactor addressing, voltage adjustment, waveform selection, clock adjustment and simple execution control (looping, conditionals, etc.). When used to create a Stimulus Program, execution of the instructions provides fully programmable voltage pulses at the tactor array/IOD limited only by the underlying hardware implementation.

3.3.1.2 VM State

The virtual machine state is outlined in detail in Appendix B – Virtual Machine State Definition. In order for the virtual machine to execute the instructions in a Stimulus Program, an associated virtual machine state is maintained. The state variables are referred to as „registers' since they serve the same purpose as processor registers for the virtual machine. These registers are broken down into several subsets; timing registers, loop control registers, address registers, voltage registers, count registers, block voltage registers, loop control

registers, waveform registers and hardware specific configuration registers. Stimulus Programs can use these registers to affect how the voltage at a tactor is changed over time.

3.3.1.3 Stimulus Programs

A Stimulus Program defines a list of instructions designed to produce a specific stimulus timing pattern at the tactor outputs. Stimulus Programs define exactly how the tactor outputs will be adjusted over time based on values stored in the VM State registers and the master clock rate. The stimulus timing and voltage output features are limited only by the underlying hardware capabilities such as maximum clock speed and stimulation power supply.

3.3.1.4 Hardware Specific Features

For each platform for which the virtual machine is implemented, a small set of instructions must be implemented uniquely based on the underlying stimulation hardware. For example, a WG-C200 device uses a single DAC channel to adjust voltage output and a Multiplexer to select the single tactor that will receive the voltage output. In order for the Stimulus Program to adjust voltage on the platform, custom code must be implemented to communicate with the DAC and Multiplexer. The HD Controller voltage output cannot be adjusted directly, however it has the added feature of custom waveform.

3.3.2 HD Controller

In order to support high density arrays, a controller was designed to allow parallel boards to drive a set of simultaneously-firing tactors, synchronized by a master clock. The implementation developed for this project utilizes a Gumstix ultra-mobile single-board-computer attached to a custom-fab board containing an FPGA, SRAM and associated drive electronics to drive 100 tactor outputs simultaneously at up to 10MHz.

The boards communicate with the workstation, acting as server, via 100Mbit Ethernet. Software on each Gumstix board executes a client application. To drive tactors, each board has a 100 pin interconnect onto which a ribbon cable can be attached. On the other side of the ribbon cable, a number of different array configurations can be connected depending on the requirements of the experiment. For small linear arrays, a subset of the boards may be used to drive a small number of tactors (e.g. 100 tactors can be driven with a single board). For higher density arrays, any number of boards up to a total of 20 on the currently built system can be utilized to drive up to 2000 tactors.

All boards are linked by a master clock bus and one board is specified as the master to drive the master clock. The FPGA on the master board outputs a programmable PWM signal to all other FPGAs on slave boards to synchronize tactor outputs across all boards. Each board has an SRAM directly attached to the FPGA to store waveform data. Waveform data consists of X/Y/Z states (X/Y/Z states correspond to high/low/ground) for the transistor on a given tactor over time producing a “1-bit DAC” style output on the tactor when stimulation voltage is fixed. The internal clock on the FPGA provides transistor state switching at up to 10MHz when clocking waveform data from the on-board SRAM.

The virtual machine implementation on the Gumstix boards provides methods (via WGIO interface over Ethernet) to program the FPGA, load waveform data into the SRAM, set the

master clock frequency, assign waveform selections per tactor and control the stimulation power relay (on/off). The software on the Gumstix also provides feedback to the workstation via a simple web-based interface (HTTP). The web interface provides feedback as to the status of the virtual machine and has been used for debugging and verification that the intended waveforms are being sent to the tactors.

3.3.3 WG-C200

To support early experiment execution using available hardware, custom software/firmware was developed for the BrainPort Balance Device C200. A device executing the custom software/firmware is referred to as WG-C200. The WG-C200 device is capable of stimulating a single tactor at a time when used with discrete IODs (one wire per tactor) or up to 4 tactors at a time when used with row/column based arrays. Voltage output level is adjustable by a DAC and the active tactor is selected using a multiplexer (4 DAC channels are used on row/column arrays).

The WG-C200 device communicates using the WGIO protocol (see Appendix C – WGIO Packet Definitions) with the workstation via an RS232 serial cable @ 115200 baud. Up to 100 tactors can be driven when connected to the 120 pin connector on the device (for discrete arrays). Row/column arrays can be driven with a row/column adapter and an appropriately programmed device (supports both 18x18 and 25x25 row/column based arrays). For small linear arrays, a subset of the 100 tactor outputs may be used to drive a small number of tactors (e.g. 10 tactor linear arrays). The DAC can be adjusted in timing increments down to 10µsec to produce a

- DAC and Waveform Timing
- Virtual Machine Implementation

3.4 Software Modules

The software modules developed for the experiment system can be broken into two subsections, pc-based (workstation) and embedded (HD Controller). The windows software applications provide an interface to the researcher and/or developer for executing experiments (Experiment Controller) and testing system operation (HD Diagnostic Utility).

3.5 Workstation PC Software Modules

3.5.1 Experiment Controller

The Experiment Controller application reads configuration from a Trial Configuration file (see the Data Formats section for more details). The researcher selects an experiment (with a corresponding Trial Configuration file) and steps through the software. Experiment specific parameters are entered by the researcher and the subject is presented with a set of trials for which they respond using an input device. The Experiment Controller software records the subject response for each trial and generates an experiment report upon completion. In

order to present trials to the subject, the Experiment Controller communicates with the HD Controller sending it trial-specific parameters which determine the stimulus pattern and waveforms used, Figure 18. Experiment Controller also controls logic and stimulation power supplies for the HD Controller via RS232 serial link.

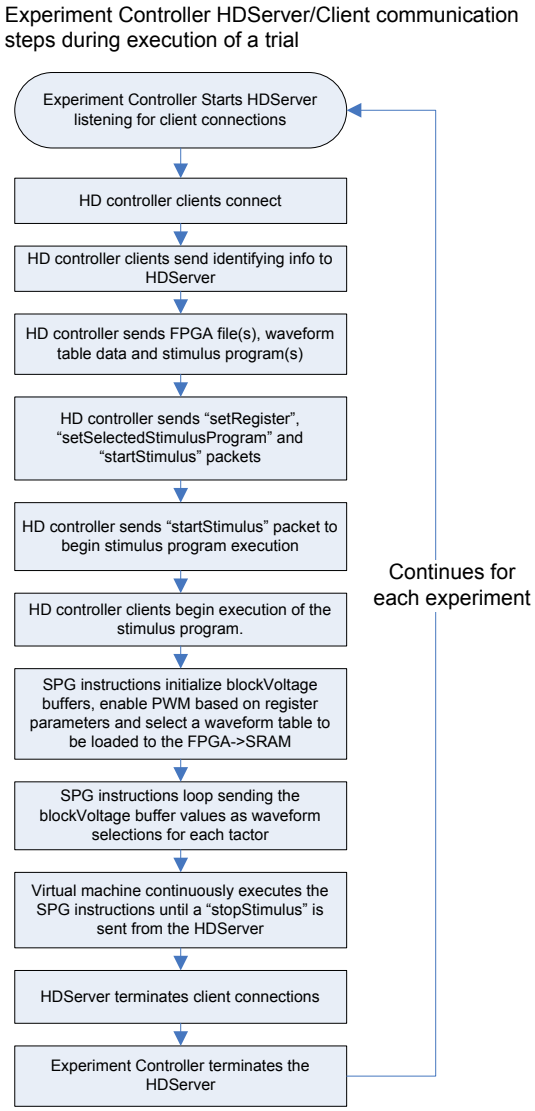


Figure 18. HD Server/Client Communication

3.5.2 Utilizing the VM to Present Trials

The „Virtual Machine' running on the HD Controller system (see the Virtual Machine section for more details) controls communications with the on-board FPGA/SRAM and sequencing of tactor selections to the attached IOD. This is accomplished through execution of a Stimulus Program in a scheduled run-to-completion scheme. Stimulus patterns and timings are defined as parameters to the Stimulus Program designed for a particular experiment. For

each trial in an experiment, the Experiment Controller sends down appropriate stimulus parameters to cause the Stimulus Program to present the intended stimulus to the IOD.

3.5.2.1 Subject Input Devices

Two forms of subject input device are possible with the Experiment Controller; the hand-held controller and the numeric keypad. The Trial Configuration file for a given experiment defines which subject input device is to be used.

3.5.2.2 Power Supply Control

The HD system includes two programmable power supplies; the logic power supply (powers logic circuits on the HD Controller boards) and the stimulation power supply (powers the waveforms to the IOD).

3.5.2.3 Platform Specific Operations

The Experiment Controller contains several features specific to the WG-C200 platform such as serial port communications and use of „DAC' values as intensity control. It also includes features specific to the HD Controller system such as power supply control and ramping features, support for waveform data transfer and FPGA file support.

3.5.3 HD Diagnostic Utility

The HD Diagnostic Utility began as a utility to visualize Trial Profiles (see Trial Configuration section for more details) to ensure accuracy when developing tactor selection patterns on high density arrays (up to 2000 tactors). This utility provides a method to select waveforms per tactor in a similar fashion to a paint program and allows importing of images to create a Trial Profile. Other features include communication with HD Controller boards and functions to test operations such as sending waveform data, FPGA data or Stimulus Program data to the board(s).

3.5.4 HD Controller Library and the WGIO Protocol

The HD Controller Library implements the windows side of the WGIO Communications Protocol. This protocol provides a set of packet definitions allowing Windows applications to command the HD Controller to start/stop stimulation, update the Waveform Definitions, upload an FPGA Program file, update Stimulus Programs and assign many other parameters affecting how stimulation is presented to the IOD. The WGIO protocol provides a handle into the state machine of the Virtual Machine executing on the HD Controller boards. For a detailed list of WGIO packets, see Appendix B – WGIO Protocol Packet Definitions. The HD Controller Library provides an event-based I/O model to the parent application and implements a socket-based communications layer to the HD Controller boards via Ethernet acting as a server in a client-server model.

3.6 HD Controller Board Modules

3.6.1 Gumstix Platform

Each HD Controller board requires a microprocessor to configure the FPGA to sequence the tactor outputs and communicate with the PC Workstation. For this task, a „Gumstix' brand single-board computer has been chosen for its speed, size and versatility in communications methods (Ethernet, serial, address/data bus, etc.). The board includes a 32-bit Marvell PXA270 processor running at 600 MHz with 128MB SDRAM and 64MB flash. The board runs embedded Linux providing TCP/IP communication and Compact Flash support for ease of development and integration. The FPGA is connected to the PXA270 via its Address/Data bus as well as a JTAG interface from which the Gumstix board programs the FPGA during the boot process.

3.6.1.1 HD Client Application

The primary software application running on the Gumstix platform is the HD Client application. This software implements the virtual machine, programs and configures the FPGA based on remote TCP/IP communications via the WGIO protocol and provides an HTML based status web page. This software maintains communications (as client) with the Experiment Controller (as server) on the PC. As an experiment is run, the Experiment Controller sends commands via the WGIO protocol to the HD Client application and the state of the FPGA is updated to reflect the commanded changes. These changes to the state of the FPGA are moderated by the virtual machine as it ticks through scheduled run-to-completion steps of a selected Stimulus Program.

3.6.1.2 Client Diagnostic Application

The Client Diagnostic application was developed in the early stages of testing the FPGA to provide an easy interface to changing memory locations before the full „HD Client' application was developed. Features include control over PWM output of the FPGA, waveform selection per tactor, loading waveform data from a file to the SRAM attached to the FPGA and LED output control. This utility is mainly useful for debugging/troubleshoot HD Controller boards exhibiting unexpected behavior.

3.6.1.3 Virtual Machine Implementation

The implementation of the virtual machine (VM) on the Gumstix platform provides implementations of all "general purpose" and several hardware dependent instructions. Each HD Controller board provides a trigger input which triggers execution of the virtual machine "ticks". The primary instructions that support tactor output on the HD system are related to waveform selections for each tactor via the Block Voltage registers, Master Clock/PWM frequency control via the Tick Unit register and control of starting/stopping stimulus programs to sequence waveform selections.

3.6.1.4 Ethernet Communications

The set of HD Controller boards each has a standard Ethernet jack on it attached to the Gumstix board controlling it. These Ethernet jacks are connected to a 24 port switch to form

a local network along with the workstation PC and the hand-held controller. The Experiment Controller (as server) communicates with each board individually (as client) via TCP/IP. The Experiment Controller (as client) communicates with the hand-held controller via TCP/IP.

3.6.1.5 DHCP server

The PC Workstation runs a simple DHCP server that supports fixing IP address to MAC address for each HD controller board. The subnet used for the local communications is 172.16.5.0/255.255.255.0. The hand-held controller address is fixed at 172.16.5.1 and the PC workstation is fixed at 172.16.5.5. The HD Controller boards are assigned IP addresses sequentially board 0 through 19 respectively numbered 172.16.5.10 through 172.16.5.29.

3.6.1.6 PC to HD Client Connections

Upon booting up and running the "HD Client" application, each HD Controller board attempts a TCP/IP connection (as client) to the Experiment Controller (as server) on the PC workstation on TCP. Upon connecting, the client communicates via the WGIO protocol and waits for commands from the Experiment controller.

3.6.1.7 HHC to PC Connection

Upon booting, the hand-held controller listens (as server) for connections from the Experiment Controller (as client). Once connected, the hand-held controller sends ASCII formatted text packets reporting the status of the slider, knobs and buttons as states change. The Experiment Controller can use this data to record a subject's response to a stimulus.

3.6.1.8 Linux Kernel Module and Interrupts

To maintain synchronized operations across boards, an interrupt is triggered with each tick of the Master Clock/PWM line.

3.6.1.9 WGTrigger Kernel Module

The Master Clock/PWM line is used to synchronize operations across HD Controller boards. This line triggers both the FPGA to start a waveform pulse and the PXA270 on the Gumstix board via a GPIO pin to tick the VM. A Linux kernel module (wgtrigger.ko) has been developed to monitor GPIO 22 to which the Master Clock line is connected and trigger an interrupt on the rising edge. This interrupt triggers the kernel module to update waveform selections in the FPGA via writes to the Address/Data bus and signal the virtual machine to execute its next "tick" in its currently selected Stimulus Program.

3.6.1.10 /proc Filesystem

The wgtrigger.ko kernel module utilizes a custom file /proc/wgtrigger to provide a pipe for communication between user and kernel space. The kernel module uses it to signal the HD Client application to execute the next VM tick. The HD Client application uses it to update the set of waveform selections for each tactor to be presented on the next Master Clock/PWM tick.

3.6.2 Hardware Interconnects

3.6.2.1 Address/Data Bus

The FPGA and PXA270 are connected via a 26 bit address and 32 bit data bus. A 16 bit Address/6x16 bit data bus attaches the 6 Static RAM (SRAM) chips to the FPGA (See TR-070054 for more details). Address locations have been defined within the FPGA for various features corresponding to logic blocks that have been programmed into it for tactor control, LED output, Master Clock/PWM generation and waveform data storage to the SRAM.

3.6.2.2 JTAG Interface

A JTAG interface (TDO/TDI/TCK/TMS) is used to program the FPGA. In order for the PXA270 to program the FPGA, 4 GPIO pins have been tied to the FPGA programming pins and a customized version of Lattice's ispvm_ui programming tool has been developed for the Gumstix platform.

3.6.2.3 Tactor Interface

Each HD Controller board has a 100 pin connector that interfaces to a 100 conductor ribbon cable. On the opposite side of the ribbon cables is an adapter providing connection to either a 10 tactor linear array (similar to that used in the WG-C200 device) or a high-density flex array.

3.6.3 Board-to-Board Waveform Synchronization

Each HD Controller board supports a total of 100 tactors. In order to support greater than 100 tactors in parallel, a set of boards uses a Master Clock/PWM signal to synchronize its tactor outputs.

3.6.4 Master Clock/PWM Signal Output

One HD Controller within the set is configured as "Master" which drives its Master Clock/PWM signal as an output (all other boards are configured as "Slave" which disconnects their Master Clock Signal driver). The signal frequency and duty cycle is programmable, typically 50% duty cycle running at <= 1kHz.

3.6.4.1 Responding to PWM Signal Input

The FPGA and PXA270 are both configured to respond to opposite edges of the Master Clock/PWM signal. The FPGA starts firing tactor output waveforms on a falling edge of this signal. The PXA270 triggers a "tick" execution in its VM and loads up waveform selections to the FPGA in preparation for the next falling edge where the output will be presented.

3.6.5 Waveform SRAM

Waveforms are generated on tactor output by sequencing the "high", "low" and "ground" transistors within the signal path. These 3 values are controlled as configuration bits that can be changed at a rate up to 10MHz by the FPGA. To toggle these lines over time, the FPGA sequences through a series of addresses on the attached SRAM modules and clocks out the data stored in the SRAM directly to the transistors for each tactor.

3.6.5.1 Writing to SRAM from the Gumstix

The SRAM consists of 6 individual chips with 16 bits of address/16 bits of data 64k deep. The FPGA provides an address window to the Gumstix for writing/reading to/from the SRAM. From the Gumstix perspective, the SRAM looks like a contiguous chunk of memory as seen below, Figure 19.

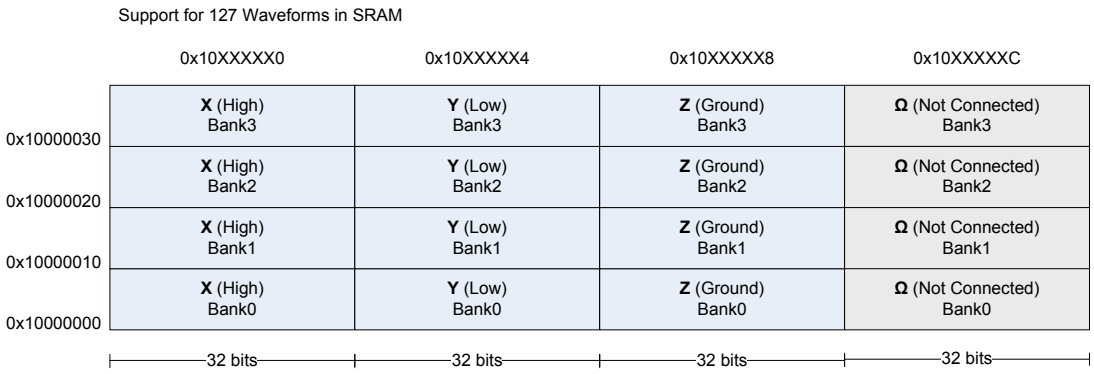


Figure 19. SRAM Memory Map

3.6.5.2 Waveform Selection Multiplexer

A section of address space 100 bytes in size @ 0x10100000 has been defined on the FPGA to specify which of the 128 waveforms in the waveform table should be output on each tactor. The Gumstix writes 25 values (32 bits each) to change the waveform that is presented to each tactor.

3.6.5.3 Clocking of Waveforms to Transistors

SRAM data starting at address 0x10000000 is clocked out to all transistor inputs (X/Y/Z) in a series of 4 clock cycles on the FPGA's 40MHz clock. On a falling edge of the Master Clock/PWM signal, the FPGA starts its waveform output sequence sequentially clocking out data from SRAM to the transistors for 800µs. The data in the SRAM is configured by the Gumstix via the address/data bus before the Master clock/PWM signal is started. By default, the first waveform in any waveform table should be programmed to select the "ground" value for all ticks within the waveform in order to ensure that the system can always disable stimulation by selecting waveform 0 for all tactors.

3.6.5.3.1 Master Waveform Clock

The Master Waveform clock runs at 10Mhz derived from the 40MHz clock rate of the FPGA. It takes 4 clock cycles to clock the X, Y and Z states out to all 100 tactors (100 x 3 bit channels). This is derived from 1 bit for X, 1 bit for Y, 1 bit for Z needing to be clocked out for 100 different tactors (3 x 100 bit channels written out 128 bits at a time in 4 clock cycles).

3.6.5.3.2 Waveform Data Length Limitations

The depth of the SRAM is 64K which determines the maximum length of a waveform that can be presented to the tactors. The configuration chosen provides storage for up to 128 unique waveforms up to 1.6ms in length. This is derived from 6 chips x 16 bits x 64K depth = 6291456 bits of data (786432 bytes) divided by 128 waveforms divided by 3 bits per tick giving 16384 ticks worth of transistor states stored. Since the waveform clock is effectively 10MHz, 16384 ticks will take 1.6384ms.

3.6.6 Power Supply Control

To power the HD Controller system, two separate power supplies are used. Each supply is plugged into a hospital grade isolation transformer to isolate the subject. Each power supply is connected to the PC workstation via RS232 link. This RS232 connection allows the Experiment Controller and other utility software to control the current limits and voltage level for the supplies remotely.

3.6.6.1 Logic Power Supply

The logic power supply provides a constant 5.0V to the HD Controller boards to power the Gumstix boards, FPGA and related hardware via on-board regulators.

3.6.6.2 Stimulation Power Supply

The stimulation power supply correlates to the stimulation level that is output at the IOD. The supply can be adjusted during an experiment to find a level that is perceived as “comfortable working level” to a subject.

3.6.7 DIP Switches/LED Indicators

3.6.7.1 FPGA Programmed Indicator

The blue LED turns on after the FPGA has been successfully programmed.

3.6.7.2 Stimulation Active Indicator

The amber LED turns on anytime the stimulation relay is open and providing stimulation.

3.6.7.3 Stimulation Supply Charged Indicator

The yellow LED on the front of the HD Controller board indicates when the capacitors are charged and ready to stimulate. This LED fades as the capacitors drain.

3.6.7.4 Master/Slave Indicator

The red LED indicates whether an HD Controller board is configured as a master or slave. If a board is configured as master, the red LED will be on and its Master Clock/PWM output will be connected, otherwise the red LED will be off.

3.6.7.5 Master/Slave Switch

The first DIP switch is used to set whether the HD Controller board will be configured as master or slave. If the board is used on its own, it must be configured as master and a jumper must be installed in the jumper block to complete the Master Clock/PWM loop-back connection.

3.6.8 FPGA

3.6.8.1 PWM Signal Programming

The Master Clock/PWM signal is programmable from the Gumstix at address 0x10300000. The PWM signal is generated using two counters which determine the “high time” and the “low time” for the signal based on the 40MHz base clock. This provides the ability to program

the PWM output with quite high resolution in the required frequency range for the system (typically <= 1kHz).

3.6.8.2 Waveform Selection Multiplexer

The FPGA has a set of multiplexers providing the ability to select any one of the 128 waveforms loaded into the SRAM for output to any tactor. This implies that each tactor can have a completely unique waveform or can be programmed to have the same waveform as other tactors based on the multiplexer input values. To specify the waveform that is used for a given tactor, an 8 bit value must be written to the corresponding location in memory location 0x10100000.

3.6.8.3 LED Indicator Controller

The FPGA provides access to changing the state of the output LEDs as bits in a bitfield at location 0x10200000.

3.7 JTAG Programming

- Lattice semiconductor provides source code for a JTAG programming module (ispvm_ui) that could be customized to work with the HD Controller platform. Four GPIO pins available on the Gumstix board were programmed as I/O and the ispvm_ui tool's source code was configured to utilize these pins for TDI, TDO, TCK and TMS.

- The HD Client application implements a command that can be triggered from the Experiment Controller to transfer an FPGA program in the form of a .VME file. Once the .VME file is transferred to the HD Client application, the ispvm_ui command line utility is called to perform the programming step placing the .VME code into the FPGA via the JTAG interface.

Deprecated Software Modules

As of the development of the HD Controller system, the WGC200 platform is no longer used to collect data. The software modules developed for the WGC200 are frozen and will be considered „deprecated' as we do not plan to further develop the software. Software modules developed for the WGC200 platform include:

Software Module	Description
WG-C200 Firmware	Provides a subset of the Wave Generator I/O (WGIO) interface enabling experiments to be developed for a modified BrainPort Balance.
WG-C200 Simulator	Simple waveform simulator running on Windows that outputs tactor stimulation levels graphically. This application was no longer needed once the WG-C200 firmware was verified to be working properly.
Array Controller API Test	Simple Windows Forms application providing a graphical interface to the WGIO protocol sending/receiving packets to/from the WG-C200 device.
Trial Configurator	This tool was used to assist in creating the two point discrimination experiment for the WG-C200 but was never finished.

3.8 Data Formats

- Trial Configuration
  - Stimulus Program
  - FPGA Program Files
  - Waveform Definitions
- Experiment Controller Report
- IOD Definition Files

4 PUBLICATIONS

Arnoldussen, A., Hogle, R., Fisher, F., Lederer, S., Rosing, M., Besta, M., Ferber, A. (2008) Spatial Resolution on the Tongue as Applied to a Prosthetic BrainPort® Vision Device. ARVO Abstr. 2898/A101.

APPENDIX A – VIRTUAL MACHINE INSTRUCTION SET

Instruction	Arguments	Description
AC		Set address to a constant value
AR		Set address to a register value
VC		Set voltage to a constant value
VR		Set voltage to a register value
RV		Set a voltage register value
RA		Set an address register value
TU		Set the time unit register
TR		Set the tick resolution register
LD		Delay a constant number of ticks
LS		Start loop with a constant count
LE		End loop, decrement count, jump to start if count > 0
ET		End Tick
RC		Set a count register value
LDR		Delay with tick count loaded from count register
LSR		Start loop with count loaded from count register
TRR		Set the tick resolution from a count register
OIC		Increment a COUNT[] register value
ODC		Decrement a COUNT[] register value
ARC		Set address from ADDRESS[COUNT[x]]
VRC		Set voltage from VOLTAGE[COUNT[x]]
RSVD1		No-op (reserved)
RSVD2		No-op (reserved)
RSVD3		No-op (reserved)
RSVD4		No-op (reserved)
BNE		Branch if COUNT[x] != 0
BEQ		Branch if COUNT[x] == 0
ELSE		Else condition for if
ENDIF		Terminator for if
RCC		Copy value from COUNT[b] into COUNT[a]
RJMP		Relative jump past n instructions
ABI		Address increment (block mode)
ABR		Reset address (block mode)
VB		Assign channelVoltage[] values from BlockVoltage[blockIndex][0-

		channelCount][tactor]
BCC		Assign channelCount from a constant
BSC		Assign blockSize from a constant
BIC		Assign blockIndex from a constant
MODE		Assign array mode from a constant
BBC		Assign blockBufferCount from a constant
ABAC		Assign absolute address in block mode from a constant
BSR		Assign blockSize from a count register
BCR		Assign blockCount from a register
BBR		Assign blockBufferCount from a count register
BIR		Assign blockBufferIndex from a count register
BCP		Assign BlockVoltage[ARG0][][] values to VOLTAGE[BlockVoltageRef[ARG1][][]]
BCPR		Assign BlockVoltage[COUNT[ARG0]][][] values to VOLTAGE[BlockVoltageRef[COUNT[ARG1]][][]
VBR		Assign channelVoltage[] values from VOLTAGE[BlockVoltageRef[blockIndex][0-channelCount][tactor]]
WVUP		Update waveform selections from BlockVoltage[bufidx][0][]
PWM		Start PWM with freq=COUNT[ARG0] duty=COUNT[ARG1]
WVTS		Activate a waveform table from the VM table list (send it to the FPGA)
BNEO		Branch ARG2 steps if COUNT[ARG0+COUNT[X]] != 0
ODCO		Decrement a COUNT[ARG0+COUNT[ARG1]] register value
BVR		Set a BlockVoltageRef[ARG0][ARG1][COUNT[ARG2]] register to ARG3
RCO		Set COUNT[ARG0+COUNT[ARG1]] register to ARG2
RCCO		Set COUNT[ARG0+COUNT[ARG1]] = COUNT[ARG2+COUNT[ARG3]]
BEQO		Branch ARG2 steps if COUNT[ARG0+COUNT[X]] == 0
BVRR		Set blockVoltageRef[ARG0][ARG1][COUNT[ARG2]] to COUNT[ARG3] + COUNT[ARG4]

APPENDIX B – VIRTUAL MACHINE STATE DEFINITION

Data Type	Name	Description
UINT32	pc	Program counter (in bytes)
UINT32	lc	Loop counter (current index into loopcount, increments when a new loop is started, decrements when a loop completes)
UINT32	tu	Time unit (defaults to microseconds)
UINT32	tr	Tick resolution (# of ticks in „tu' units between VM ticks)
UINT32	et	End tick (ends a run-to-completion series)
UINT32	dr	Delay register (holds # of ticks to delay)
UINT32[]	loopStart	Stores pc when a loop starts
UINT32[]	loopCount	Loop counts (dimension determines max # of nested loops)
UINT32[]	regV	Voltage registers
UINT32[]	regA	Address registers
UINT32[]	regC	Count registers
UINT32	ainc	0 – do not increment address, 1 – increment address (used for row/column IOD block mode)
UINT32	arst	Address reset (0 do nothing, 1 reset tactor address to 0 on next tick)
UINT32	dacval	Current DAC value
UINT32	tactor	Current tactor address
UINT32	arrayMode	Current array configuration mode 0: Discrete tactor scanning mode 1: Block tactor scanning mode 2: Discrete parallel mode 3: Block parallel mode
UINT32	addressMode	Current tactor addressing mode
UINT32	voltageMode	Current tactor voltage mode 0: Single DAC 1: Multiple DAC 2: Simultaneous
UINT32	blockSize	Number of tactors in a block for block addressing mode
UINT32	blockBufferCount	Number of block voltage buffers to allocate (corresponds to number of full "frames" of waveform selections for each tactor)
UINT32	blockBufferIndex	Index into the blockVoltage array indicating the currently selected block voltage buffer to present
UINT32	channelCount	Number of channels/blocks for multi-DAC mode
UINT32[]	channelVoltage	Current DAC value for each channel in multi-DAC mode
UINT32[][][]	blockVoltage	Array of values sized by [blockBufferCount][channelCount][blockSize] used to indicate which voltages should be applied to each tactor and/or which waveforms should be applied to each tactor
UINT32[]	blockVoltageRef	Array of indices into regV[] that can be used to copy regV[] values into a blockVoltage[][][] buffer
UINT32	fpgaFileCount	Number of FPGA files (.VME) loaded
CHAR[][]	fpgaFilename	Filenames of .VME files loaded
UINT32	waveformTableCount	
UINT32	waveformTableCount	Number of waveform tables that are loaded
UINT8[][]	waveformDataTable	Points to dynamically allocated waveform table arrays
UINT32[]	waveformCounts	Number of waveforms in each table
UINT32	waveformSizes	Sizes of each waveform in bytes

APPENDIX C – WGIO PACKET DEFINITIONS

Command	Arguments	Description
RDP		Return Data Packet
SPLS		List loaded Stimulus Programs
SPSET		Set the current Stimulus Program
SPLD		Load a Stimulus Program
SPDEL		Delete a Stimulus Program
RASET		Set one or more address registers
RVSET		Set one or more voltage registers
RCSET		Set one or more count registers
SPSTAT		Get device status packet
SPGO		Start/Resume the VM
SPHALT		Stop/Pause the VM
PINGCFG		Configure PING packets
PING		Ping packet
RESET		Reset the VM
CLEARSP		Delete all Stimulus Programs
RAGET		Get the value of an address register
RVGET		Get the value of a voltage register
RCGET		Get the value of a count register
RBSET		Set one or more block voltage buffer registers to a value
BREFSET		Set one or more BlockVoltageRef[][][] registers to a value
RBGET		Request a packet containing the value of a block voltage buffer value
CCONFIG		Client configuration packet
VMEFILE		FPGA .VME file packet
WAVETBL		Waveform data table packet
CLRDY		Client ready packet
RBREF		Set one or more values in BlockVoltageRef[] to a value from the VOLTAGE[] array

DEFINITIONS

AFRL	Air Force Research Laboratory
API	Application Program Interface
DARPA	Defense Advanced Research Projects Agency
HD	High Density
HDA	High Density Array
IRB	Internal Review Board
Tactor	Electrode on stimulation array, comparable to pixel on visual display
TUNS	Tactical Underwater Navigation Systems