A DEVICE FOR VIBROTACTILE STIMULUS DELIVERY IN MAGNETIC ENVIRONMENTS

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A thesis submitted to the faculty at the University of North Carolina at Chapel Hill in partial fulfillment of the requirements for the degree of Master of Science in the Depart of Biomedical Engineering.

Chapel Hill
2014

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ABSTRACT

Bryan M Kirsch: A Device for Vibrotactile Stimulus Delivery in Magnetic Environments
(Under the direction of Mark Tommerdahl)

Currently, the most accurate and precise method to deliver a vibrotactile stimulus is via the use of a voice coil actuator (VCA). Because the VCA uses a coil of wire contained in a magnetic field, this system cannot be used in imaging systems that rely on the use of magnetic fields. Thus, an alternative device is needed that can be used to deliver tactile stimuli in magnetic fields such as those generated by Magnetic Resonance Imaging (MRI) and Magnetoencephalography (MEG) systems. For this reason, a novel stimulus device was designed to deliver vibrotactile stimuli with variable amplitudes (up to 2mm peak-to-peak) and frequencies (ranging from 25Hz up to 200Hz) as these are the optimal stimuli for evoking activity in somatosensory cortex. To accomplish this, a system using a high-voltage op-amp and piezoelectric actuator was designed to deliver precise and accurate stimuli to the skin without being impacted by the surrounding magnetic field. Additionally, the device was designed with the intention of keeping all sensitive electronics at a safe distance from the magnetic imaging systems.

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LIST OF ABBREVIATIONS

μF	Microfarad (capacitance)
AC	Alternating Current
CNS	Central Nervous System
DC	Direct Current
DAQ	Data Acquisition
FDM	Fusion Deposition Modeling
fMRI	Functional Magnetic Resonance Imaging
ft	Foot (distance)
Hz	Hertz (cycles per second)
IC	Integrated Circuit
mm	Millimeter (distance)
MRI	Magnetic Resonance Imaging
NI	National Instruments
PC	Personal Computer
PCB	Printed Circuit Board
SVM	Support Vector Machine
USB	Universal Serial Bus
V	Volt

VCA	Voice Coil Actuator
Vpp	Peak-to-Peak Voltage

Chapter 1: Introduction

Background

Several years ago, Tommerdahl and colleagues designed and fabricated a non-invasive portable sensory based diagnostic system (Tannan et al 2007a). Initially, this system was used to investigate information processing in autism. The device ultimately showed that several protocols appeared to be sensitive to detecting differences between autism and controls. Further development showed that the results of these protocols, when analyzed via SVM (a machine learning analytical tool) was close to 90% accurate when determining if the individual performing the tests had autism. The results showed that the device, using protocols that were all non-invasive, non-noxious tests, could potentially provide valuable and cost effective information to a primary health care giver when evaluating a patient's diagnosis or efficacy of treatment. The device also established standardized sensory measurements that can be used in clinical or clinical research settings, which can be directly correlated with observations from high resolution laboratory animal studies and experimentation. Additionally, the device could be used beyond the scope of autism and potentially provide neurological information about a given disease or disability as it relates to the central nervous system (CNS).

The device operates by delivering tactile sensations to the finger tips. Initially, this device was designed to investigate cortical information processing and

one of the early findings was that there were significant differences in information processing between typically developing controls and individuals with autism (Tommerdahl et al 2007a, 2008). The protocols used were developed to specifically target mechanisms of CNS information processing, and the protocols could target diminished capacities known to exist in autism from phenotypic results of physiological and anatomical studies. Changes from autism are systemic in that large scale changes to cortical information processing in the CNS occur throughout the cortex.

With the device having been shown to provide results that distinguish the two populations, the next question to be addressed was whether this same approach could be used to obtain information that could be used in a similar fashion for a wider range of neurological disorders. If the device showed effectiveness in detecting systemic alterations for one neurological disorder, could it also detect the systemic cortical alterations for various other neurological disorders as well? Proof-of-concept studies in a number of clinical research areas demonstrated that these metrics are not only sensitive to the systemic alterations of autism; in fact, it was sensitive to systemic cortical alterations in general and effective across many populations. A key metric is adaptation, which was found to be significantly altered in many populations. The result was in line with expectations as various mechanisms in the cortex play significant roles in adaptation.

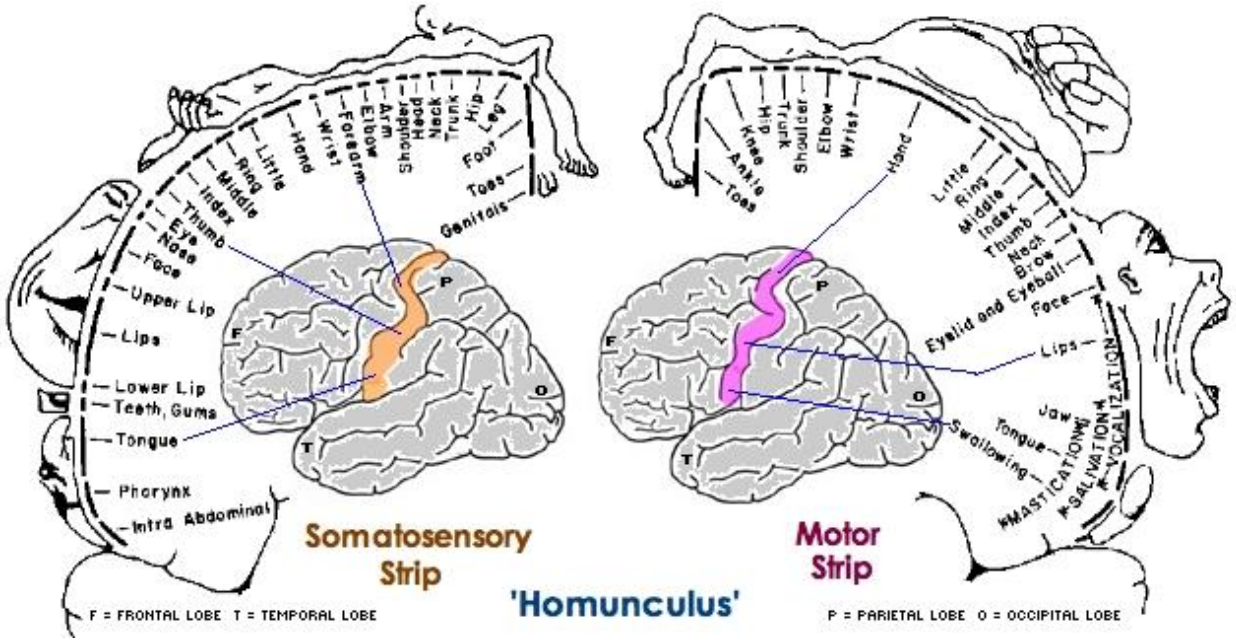

Figure 1 - Homunculus. Somatosensory cortex topography (left), known as the somatosensory homunculus. Spatial organization is organized in such a way that sensory neurons are mapped according to their location and spatial area. Higher density regions occupy larger areas of the central sulcus (primary somatosensory cortex).

To understand how these measurements can be quantified, the organization and physiology of the somatosensory cortex must first be explained. The topography of the cortex is organized into a homunculus (Figure 1), with spatial information organized locally in each area. The system is not organized evenly, but rather roughly equal to the density of sensory neurons on the skin. This leads to the topography being organized roughly proportional, with higher density areas such as the hands and face having a larger area of the cortex than lower density areas such as the arms and legs. Furthermore, this spatial mapping of the general regions also applies to the individual neurons, with adjacent neurons on the skin mapping to adjacent cortical columns in the primary somatosensory cortex. These columns are organized in such a way that the each column has a negative effect in the activation of adjacent columns. This physiological function can be roughly mapped as a sinc function (Figure 2), where excitation of one column inhibits

adjacent columns, giving rise to the term “lateral inhibition”, and is a key element of adaptation. The device gives a quantitative measurement of the amount of adaptation an individual has when responding to various somatosensory stimuli.

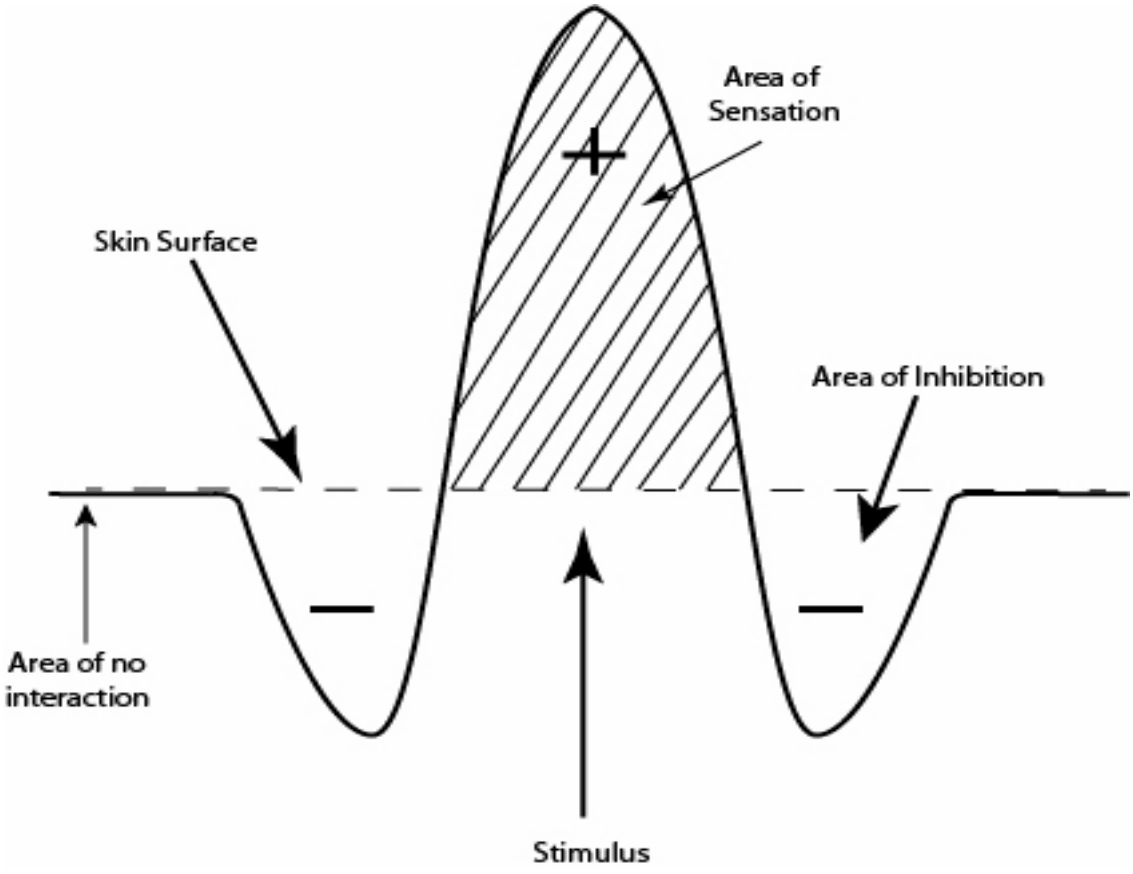

Figure-2. Diagram of lateral inhibition. An area receives a stimulus, exciting the region in the primary somatosensory cortex. This excitation inhibits the area surrounding it, making it more difficult for those neurons to experience excitation as well.

With the concept proven, the device has gone through several stages of development. The current iteration is the CM-5, a 4 point stimulator which delivers stimuli via Voice Coil Actuators (VCAs). The VCA was designed using Lorenz’s Law to accurately control vibrations by controlling the current flowing through a coil of wire in a constant magnetic field. To achieve a constant magnetic field, a series of neodymium magnets are placed around the coil of insulated wire.

Figure 3 – Magnetic resonance imaging (MRI) machine. A state-of-the-art 3T 70cm MRI machine. 3T is the standard for head MRI, providing fast imaging and high resolutions. Shown is the MAGNETOM Skyra manufactured by Siemens. Image from http://usa.healthcare.siemens.com/magnetic-resonance-imaging/3t-mri-scanner/magnetom-skyra.

There are several imaging modalities which are effective for mapping soft tissue. In particular nuclear Magnetic Resonance Imaging (MRI) provides excellent resolution and contrast for brain tissue. MRI uses a magnetic system to orientate the water molecules of a region in a direction (Figure 2). Following this, the molecules are allowed to "relax" into their normal random orientations. This information is used in several images, with two main physics-based images: Longitudinal (T1) and Transverse (T2) (Figure 3). For T1 imaging, the relaxation

rate is measured as a value of the spin of the hydrogen in the tissue when compared to the environment. T2 imaging records the net magnetization value perpendicular to the magnetic field. These two images give distinct anatomical information, with grey matter, white matter, and cerebral spinal fluid (CSF) having distinct relaxation rates that provide excellent contrast. For physiological information, function MRI (fMRI) is typically used. In fMRI, two images of the same anatomical region are compared to one other, with a region of activity having differing relaxation rates between the two images. Typically, this is the result of glial cells absorbing water from the surrounding interstitial space as they respond to activity in the adjacent neurons.

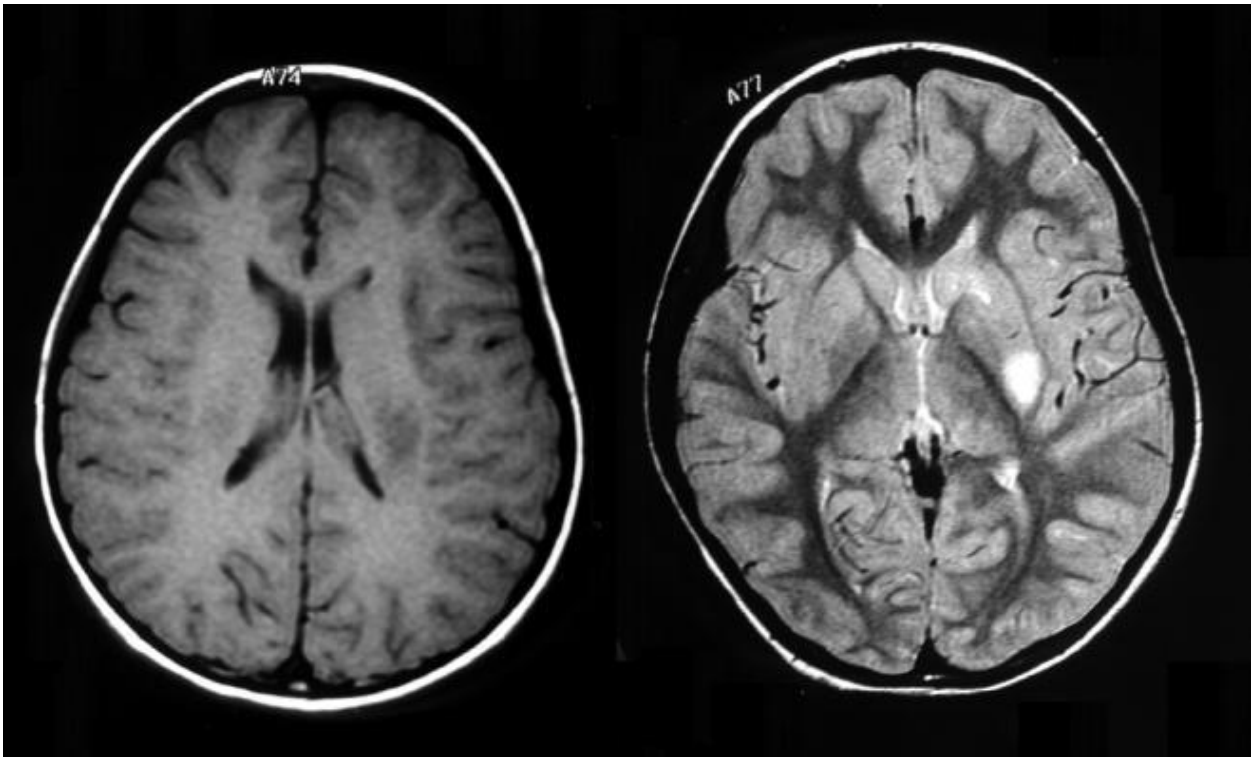

Figure 4 – Comparison of T1 and T2 weighted images. T1 image (left) compared to T2 image (right). Each of the three tissues main tissues in the brain have distinct contrast values, making MRI imaging excellent for brain imaging. Image from http://www.hawaii.edu/pediatrics. Used under Fair Use.

With MRI providing excellent anatomical and physiological data, and the CM device providing neurological data, using the CM device in conjunction with an fMRI would provide physiological info about the somatosensory cortex in an individual in a non-invasive, non-noxious, manner. The key problem lies in making the CM device magnet compatible. The VCAs use a magnetic field to deliver the physical stimuli, which means that the entirety of the VCA must be reconstructed in order to become magnet compatible. There have been devices designed to deliver vibrotactile stimuli to a subject while acquiring an fMRI (Harrington et al 2000). One uses pneumatic pressures to make the system magnet compatible (Francis et al 2000). However, these systems do not have the wide range of functions that the CM device has, and a new stimulus delivery system must be designed. This system must be able to work with current CM software and deliver the wide range of protocols and stimuli that have come to be used by the research group.

CM Device

Previous research has led to several device designs, none of which are magnet compatible. To summarize the most recent design iteration, the device makes use of rapid-development technology to allow for rapid direct manufacturing, which allows for rapid changes in device development between device iterations. The current device uses a 12V external power supply for use in the VCAs, and a 5V USB power supply to power the custom-designed mainboard and microcontroller. For more information/details of the device design, see Holden 2013.

Hardware. The current model uses the previous model's head unit as a self-contained entity. This head unit is direct manufactured from ABS plus, by fusion deposition modeling (FDM) on a StrataSys Dimension bst 1200es (StrataSys, Inc., Eden Prairie, MN). The cylindrical trays forming the disks of the head unit are CNC machined from 1" thick Acetal (Delrin) plate. All housing and mechanism components and assemblies were solid modeled prior to fabrication using SolidWorks solid modeling software (SolidWorks Corporation, Concord, MA). The custom electronics was designed using Eagle PCB (Camsoft,) software. This microcontroller board is controlled by a PIC32 microcontroller. This microcontroller interfaces with a personal computer through USB, and outputs to each of the VCA coils are analog sinusoids of desired frequency with a maximum peak-to-peak voltage (Vpp) of five volts. To accomplish this, the system requires an external power supply which is rectified and translated through motor-driver ICs.

Software. The custom software on the host computer is written in javascript, with protocols and additional functions written in a derivative language called coffeescript. The software is designed to allow for customization of the desired stimuli, as well as making it intuitive and aesthetically pleasing. The software is published as a chrome application under the title "Brain Gauge', requiring an installation of Google Chrome software on the host computer. The software interfaces with the PIC32 microcontroller through a USB connection. The PIC32 interprets the packets received from the host computer, and the custom electronics respond by outputting desired analog signals. These analog signals are of a frequency, amplitude, and time length specified by the customizable protocols from the Brain Gauge software.

CHAPTER 2: A MAGNET COMPATIBLE DEVICE

Introduction

A previous research model of a magnet compatible version exists (designated CM-3). This model is large and expensive, with two power supplies, custom built electronics, and an expensive data acquisition (DAQ) board. This device, while portable and proven to achieve diagnostic data equivalent to that of its VCA predecessor, is cumbersome and costly to manufacture. Elimination of these large and ultimately unnecessary components is required to make a magnet compatible device economically feasible for diagnostic use.

Microcontroller and Electronics

The previous research model (CM-3) is based on the CM-4 custom-built electronics. These models used custom electronics designed using free CAD software from ExpressPCB (www.expresspcb.com). The printed circuit boards (PCB) were manufactured using the resulting CAD files, also by ExpressPCB. The hybrid circuit includes signal amplifiers, an analog controller, and a tunable analog PID controller. This hybrid circuit is interfaced via four parallel pin connectors (2 banks of 50 pins for digital signals and 2 banks of 34 pins for analog signals) to an internal NI-USB-6259 (DAQ) board. The DAQ board then interfaces via a USB connection to any standard PC running Microsoft Windows XP or later.

The custom electronics of the CM-5 are much more compact (Figure 5). Implementation of a CM-5 mainboard and microprocessor eliminates the costly third-party NI DAQ from the device design. Additionally, the other functions of the previous custom electronics can be done by the CM-5, with equally accurate output delivery and feedback from the VCAs. The custom built CM-5 board also made use of a 16-bit data acquisition IC. This IC, in conjunction with the PIC32 microcontroller, ensured that all data collected was equally precise and accurate to that of its NI DAQ predecessor.

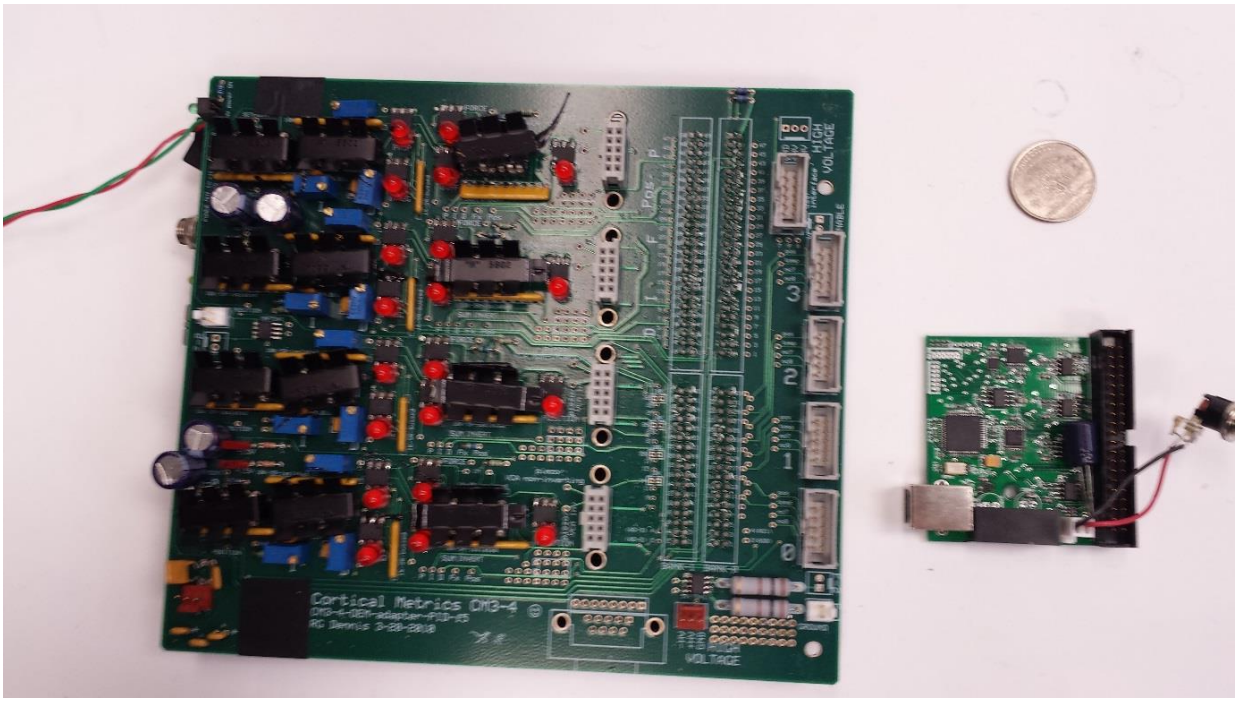

Figure 5 – Comparison of custom electronics. CM-4 custom electronics and DAQ (left) compared to the custom electronics of the CM-5 (right). The CM-5 electronics have comparable outputs and feedback sample rates. Quarter for scale.

With the CM-5 electronics being comparable to the more expensive CM-4, replacing the large and expensive electronics in the CM-3 with architecture similar to that of the CM-5 was a logical step. With this improvement made, the only

antiquated electronics still remaining is a bipolar push-pull high-current op-amp output stage and power supply.

Power Supply

The power supply is based off of the original CM device architecture. It takes the 110V AC power supply, and rectifies it into a 15V DC power supply. Additionally, the 110V AC is stepped-up by a 2:1 transformer to create a positive and a negative 180V DC power supply. These two DC power supplies are necessary for the analog operational amplifiers to achieve the required step-up voltage necessary for the piezoelectric actuators that replace the VCAs. The power supply size is large, with the length and width of the combined power supplies nearly equal to that of the NI DAQ board. With the controller electronics miniaturized by their replacement with a CM-5 microcontroller board, the power supplies are now the limiting factor of the size of the device.

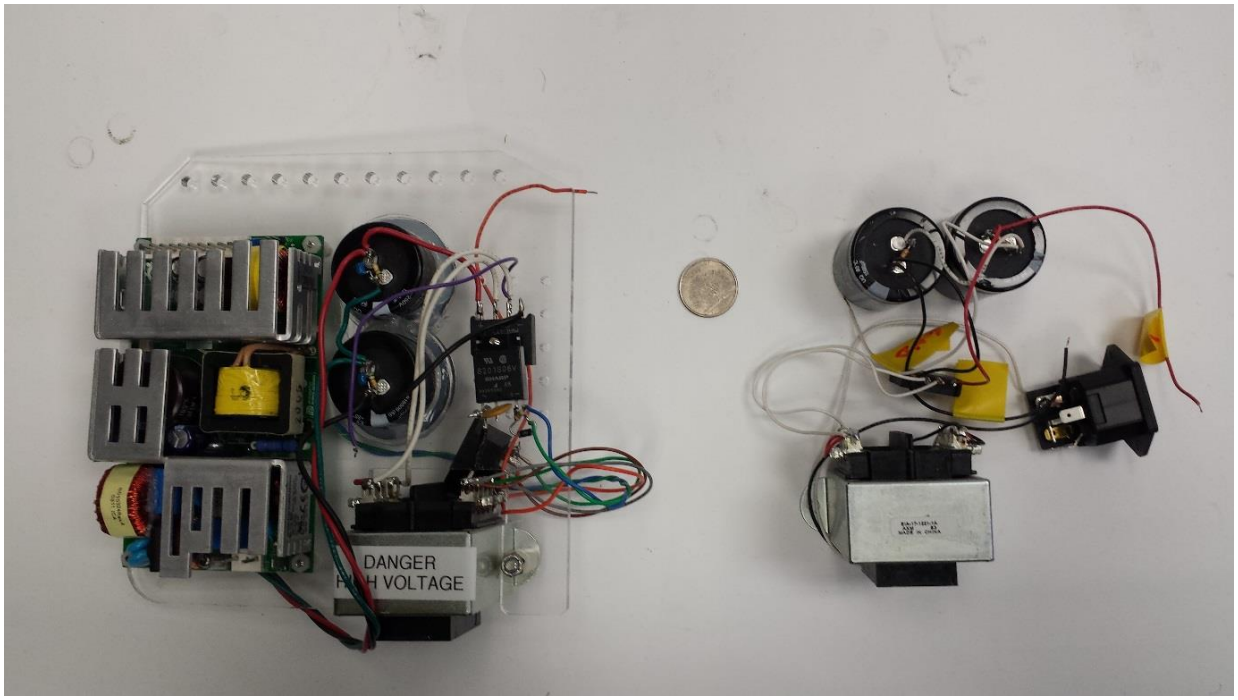

Figure 6 – Comparison of power supplies. Research Model custom built power supply (left) compared with the reduced-size power supply (right). The elimination of the 15V supply is essential for power and weight reduction. Further improvements can be achieved using smaller capacitor sizes and a smaller form-factor transformer. Quarter for scale.

The 15V DC power supply (Figure 2) was needed by the NI DAQ and CM-4 electronics. By using the current model CM device main-board, the older custom PCBs become obsolete. This allows for the replacement of the large 15V DC power supply with a smaller, cheaper, self-contained 12V DC power supply brick commonly used by many electronics. With the 15V supply removed, the old acrylic mounting is obsolete, and the overall size of the device can be further decreased. However, the +180V and -180V power lines are still necessary, to supply the actuators with power.

Op-Amp and Piezoelectric Actuator

Typical somatosensory tests involve delivering stimuli between 25Hz and 200Hz. The maximum amplitude of the stimuli is 800 microns peak-to-peak at 25Hz (with maximum displacement from resting position at ±400 microns), which is limited by the sampling rate of the microcontroller. Thus, any piezoelectric actuator chosen must, at a minimum, function accurately at these levels. Additionally, the actuator should have a higher ceramic content, as the magnetic environment could have unintended effects such as inducing a current bias and causing an offset in resting position of the actuator. Thus, a high ceramic-content piezoelectric actuator with a maximum displacement of 1mm from the resting position was chosen.

The operation of an actuator has one end of the actuator in a fixed position. When a voltage is present across the terminals, the actuator bends with displacement measured at the unclamped end's movement from resting position when there is no applied voltage. This displacement is linearly dependent on the voltage applied, so sinusoidal voltage results in sinusoidal displacement. With long lever arms, a proportionally small displacement can be estimated to be perpendicular to that of the resting state of the lever arm. Using this knowledge, a four-arm bar linkage used in the VCAs of the standard CM devices was altered. This new VCA housing consists of an anchor for the fixed end of the actuator at the anchored part of the linkage, and a site that allows for silicon adhesive to be applied to the distal end of the actuator at the other end of the four-arm bar linkage. The design ensures that the probe tip moves linearly, with the actuator's displacement driving the sinusoidal motion of the probe tip.

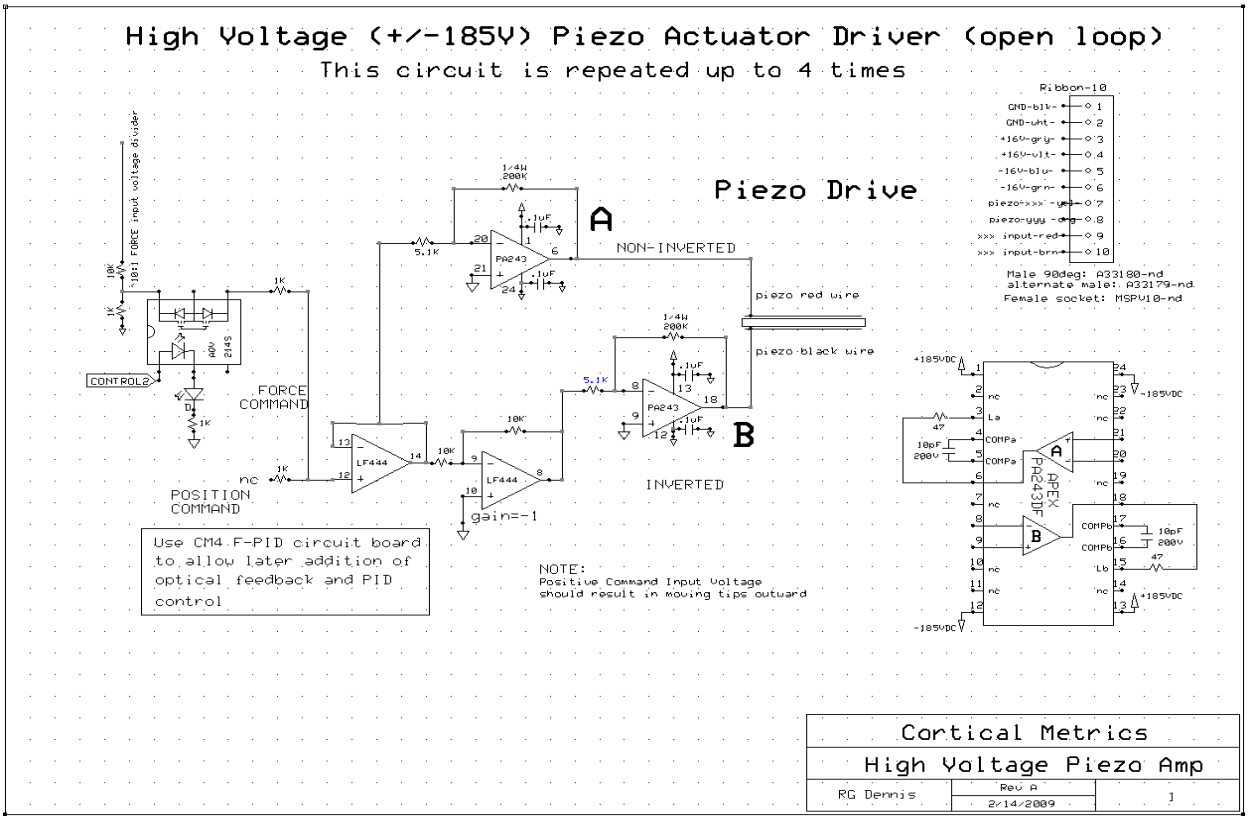

Figure 3. Schematic of linear operational amplifier. The gain of 40 is achieved by using an inverting operational amplifier circuit. This displaces the sinusoid by 180 degrees. The one part of the signal is inverted again to achieve the complimentary 180 degree sinusoid. Original Schematic by Dr. Robert Dennis. Current Schematic and modifications by Bryan Kirsch.

To achieve the maximum voltages necessary across the terminals of the actuator, linear analog operational amplifiers are used (Figure 3). With supplied voltages of +180 and -180, and current supplied from large 1500 μF, the operational amplifiers can accurately amplify an input sinusoid up the 200Vpp. The CM-5 custom electronics outputs a sinusoid of a maximum of five volts peak-to-peak, which implies that an amplification gain of 40 is required to reach the maximum voltage of 200Vpp.

An additional problem presents itself. The 400 micron maximum displacement is only attainable when there is a 200V potential across the terminals

of the actuators. A 200Vpp sinusoid only reaches a maximum potential of 100V in relation to the ground state. To overcome this problem, it is necessary to realize that the voltage potential across the actuator's terminals is simply in relation to a positive and negative terminal, where the resting position is in relation to a voltage potential of zero volts. This means that a 100V potential can be achieved with 100V across the positive terminal with the negative terminal at the ground state, -100V across the negative terminal with the positive terminal at the ground state, or any summation of positive and negative voltages cross the two terminals such that the result is equal to 100V. Thus, it is possible to create two sinusoids with a 180 degree phase difference and sum them across the terminals. This means that for a sinusoid with a peak of 100V (200Vpp) can be summed with a sinusoid 180 degrees out of phase at the other terminal to achieve the 200Vpp difference that is necessary to achieve the required displacement. This function ensures that the magnet compatible device will deliver stimuli equal to that of the standard device without requiring any changes to the base code of the CM5 device or the Brain-Gauge software.

The sensitive electronics must be safe from the magnetic flux of the MRI environment, and to accomplish this a long 200ft serial cable connects the operational amplifiers to the head unit where the piezoelectric actuators and probe tips are located. This ensures that the power and custom electronics can be placed in the protected environment where the MRI electronics and researcher are located, allowing ease of control for the researcher to deliver stimuli and monitor patient conditions.

CHAPTER 3: FUTURE DIRECTIONS

The magnet compatible device presented here has the potential to be improved upon. Power efficiency can be increased. Physical device size and weight could be further decreased. Manufacturing costs can be decreased significantly. All of these implementations would increase the viability of this product for diagnostic and research adoption.

One area of improvement would be a redesign featuring the ARM chipset in place of the PIC chipset. Implementation of this chipset would reduce manufacturing costs without any decreases chip performance. In fact, the ARM chipset has various performance increases over the PIC chipset in use. Additionally, the ARM chipset is lower power than the PIC chipset, decreasing total power consumption of the custom electronics.

The device size is still very large overall, with a bulky 2:1 transformer and large 250V 1500μF capacitors. Switching to a toroid transformer and decreasing capacitor sizes would go a long way to improving the size and weight of the device. Decreasing the capacitor size also has the added benefit of reducing the discharge time of the capacitors, making handling the sensitive electronics safer overall. An even great improvement would be the implementation of piezoelectric step-up drivers – compact ICs which step up the input voltages on demand, further reducing the power storage and size of the device while simultaneously increasing safety. Additionally, moving the magnet compatible device electronics at the same

pace as the standard CM device will ensure that any custom electronics size improvements directly relate to the size if the magnet compatible device as well.

Finally, manufacturing costs can be improved by implementing all of the design options previously mentioned. By keeping the magnet compatible device update with the same electronics used in the standard model, overall manufacturing costs will decrease, not to mention that ARM chipsets are significantly cheaper than the currently used PIC chipsets. Additionally, power supply costs can be significantly decreased just be implementing smaller capacitors. The housing manufacturing costs will only decrease as size is decreased, as less material used in housing construction directly translates to manufacturing costs.

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