CHRONIC MICROELECTRODE RECORDING ARRAYS

Quarterly Report

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CHRONIC MICROELECTRODE RECORDING ARRAYS

Executive Summary

This contract seeks to develop wireless microsystems for chronic multi-channel recording in the motor cortex of primates. The approach we are taking uses active or passive multi-channel two-dimensional silicon probes containing 16-64 sites each, arranged in three-dimensional arrays. The probe output signals are routed to a hermetically-sealed circuit package using multi-lead silicon- or polymer-based microcables. This circuitry identifies neural spikes and passes the spike occurrences to the outside world over a bidirectional wireless link that derives power and control signals for the implant from an externally-supplied RF carrier. The implanted circuitry can also be used to output a full analog representation of the neural activity on any single site.

During the past quarter, work has moved forward on the design of the electrode interface electronics for the cortical microsystem, on the testing of the wireless interface, and on the implant housings. The recording amplifiers have been redesigned to make them programmable in terms of their gains, offsets, and low-frequency cutoffs. Gain is programmable between 100 and 1000, and both the offset and the cutoff frequency are set using 12b analog-to-digital converters. These ADCs resolve 0.7mV in setting these parameters. Sixty-four amplifiers have been integrated on a single 3.1mm x 4.8mm chip that dissipates only 3.2mW. This new amplifier chip replaces four of our earlier 16-channel chips and offers increased flexibility. The chip is in fabrication now in a commercial foundry and will be returned for testing later this month.

Testing has continued on our neural signal-processing chip and on our wireless interface chip. The most important result from this testing is the discovery that our wireless chip, which had been thought to be non-functional in the forward telemetry mode, is in fact fully functional. Thus, all of the electronics for the intended cortical microsystem is operational. Input command data is supplied by FSK-modulating the RF input power carrier between 4MHz and 8MHz, with the input circuitry correctly recovering data and clock. The reverse telemetry circuits, which transmit the recorded neural signals to the outside world, are also fully functional as earlier reported, with an output carrier frequency that is programmable between 72MHz and 194MHz. Using a distance of 1mm between the transmitter and the receiver antennas, the received signal amplitude was 650mV with a signal-to-noise ratio (SNR) of 12.5. On the eventual SPIDER implant platform, a signal-to-noise ratio of at least 5 is expected. On the neural processing chip, the spike thresholds can be varied over a range of \pm 500mV, which is more than adequate.

The development of both the MINI and the SPIDER implant housings continues. During this past quarter, the height of the MINI chamber walls was reduced from 0.45" to only 0.05". The reduction in the wall height offers better a better view of the connectors while attaching the cables for recordings and also reduces the overall weight of the device since the lid, now bearing the majority of the material, can be made out of a lighter material. All parts of the housing are still machined out of commercially pure titanium. In the next iteration, we are planning to move to the use of polypropylene to reduce the possibility of bacterial build-up and produce a package that is easier and faster to machine. We should be ready for primate implants in both housing configurations when the full microsystems are available this fall.

Activity Summary

During the past quarter, we have continued to work on the various components that will be required to realize wireless implants of 64 recording sites in primate motor cortex. The target SPIDER microsystem is shown in Fig. 1. The implanted probes connect to a



Fig. 1: Perspective view of the SPIDER cortical implant microsstem.



Fig. 2: Components of the cortical microsystem.

chip is now in fabrication in a commercial foundry.

- The forward telemetry portion of our wireless interface has been more extensively tested and has been found to be fully functional; thus, all chips needed for the cortical microsystem are in place. Work to complete the wireless and data recording/display portions of the system are underway.
- We have continued to develop our older MINI implant housing in parallel with the newer SPIDER. The primary recent change to this design has been to decrease the height of the housing walls from 0.415" to only 0.05". The reduction in the wall height offers better a better view of the connectors while attaching the cables for recordings and also reduces the overall weight of the device since the lid, now bearing the majority of the material, can be made out of a lighter material. All parts of the housing are still machined out of commercially pure titanium. In the next iteration, we are planning to move to the use of polypropylene to reduce the possibility of bacterial build-up and produce a package that is easier and faster to machine.

hermetic subcutaneous electronics package using polymeric cables. This results in a reliable implant with a short transcutaneous wireless link for power The overall microsystem, and data. shown in Fig. 2, consists of the recording probes, a silicon or polymeric cable, site selection and amplification circuitry (eventually on the probe), a neural spike detector to separate the spikes from background noise and digitize them, and a wireless interface chip that transmits data out and derives power and command signals from an external RF system.

During the past quarter, the following activities went forward:

Our recording amplifier was redesigned to make it programmable in gain, bandpass, and offset. Sixty-four of these amplifiers have been integrated on a single chip, replacing four earlier 16-channel chips. The 64-channel

Research Results and Discussion

1. Development of Probe Interface Electronics

A 64-channel digitally-programmable amplifier chip was designed in a 0.5μ m process and was submitted to the MOSIS foundry service in June 2006 for fabrication. This chip replaces four earlier 16-channel amplifier chips and includes programming capability for gain, offset compensation, and low cutoff frequency. The gain is programmed by switching different values of feedback capacitance as shown in Fig. 3. Six bits are used for setting the gain, resulting in signal amplifications from 100x to 1000x in increments of 100. The ability to program the gain provides an opportunity to correct for process variations when the output voltage is clipped at the supply rails.



Fig. 3: Block diagram of the amplifier programming capability.

All 64 channels on the chip share two 12-bit digital-to-analog converters, one to set the low-frequency cutoff and the other to compensate the offset voltage. The DAC resolution is 0.7mV. The DACs have been designed using capacitive ladders to minimize the overall power consumption of the chip. The DAC design used on this chip is shown in Fig. 4.

All amplifiers also share a common bias network, which by itself consumes about 25μ W, while each amplifier consumes 50μ W. The resulting power consumption of the entire 64-channel chip is 3.225mW. The chip size is 3.1mm x 4.8mm. The layout of the 64-channel programmable amplifier chip is shown in Fig. 5. Testing will begin near the end of August.



Fig. 4: Digital-to-analog converter using a capacitive ladder network designed for a fully-implantable neural amplifier chip.





2. Signal Processing Circuitry for the Cortical Microsystem

During past reports, we have described the development and testing of the neural processing units (spike detectors) and the wireless chip designed for the cortical microsystem. These chips accept the outputs of the electrode site amplifiers and compare the signals with user-programmable thresholds. In the scan mode, when the signal is above threshold, the address of the site where the spike is occurring is encoded as an event for wireless transmission to the outside world. In the monitor mode, the signal from any of the 64 channels is transmitted to the outside world over this same link. Both the neural processing units (NPUs) and the reverse-telemetry sections of the wireless chip have been fully functional, and performance results for them have been reported. However, it had been thought that the forward telemetry section of the wireless chip was not functional and would have to be re-designed. In further testing during the past term, we have found that this block is also fully functional, and results from it will be presented in this section. It is important to note that all portions of the intended microsystem were fully functional at the end of the original Base Period of this contract. We are now in the process of assembling final portions of the wireless links for this system. Live recordings over a period of 30 days will be obtained first using a printed-circuit-board version of this system with connectors into a MINI or a SPIDER implant package. A fully chronic implant using the SPIDER configuration will then be characterized.

Digital FSK Demodulator/Clock Recovery Block

A block diagram of this section of the system is shown in Fig. 6. It is comprised of a time-base generator oscillating at 50MHz, a divide-by-8 frequency divider, a level translator, and a digital logic block. To tolerate the relatively high voltage amplitudes received by the coil, M1 and M2 in the level-translator block are field-oxide transistors. The input signal to this block is a wideband FSK-modulated voltage switching between 4MHz and 8MHz with a bit rate of 2Mbps. A complete data packet is prepared, FSK modulated, and delivered to the circuit. Figure 7 shows the raw data packet, FSK-modulated signal at the input applied to the circuit, and the recovered clock and the demodulated data at the outputs of the circuit. This experiment was performed at the above-mentioned carrier frequency and bit rate. The input block is fully functional.



Fig. 6: Block diagram of the digital FSK demodulator/clock recovery circuitry.



Fig. 7: Experimental operation of the circuit of Fig. 6. The incoming data packet, FSK-modulated data, recovered clock, and demodulated input command data are shown.

Reverse Telemetry Back-End (RTB)

The reverse telemetry block on the telemetry chip has been tested, optimized, and characterized. Figure 8 shows an outgoing data packet passing through the RTB. In this test, the carrier frequency, which is physically programmable on the chip, is around 80MHz. Based on the experiments carried out, the carrier frequency can be set from 72MHz up to 194MHz. Using a dipole antenna on the printed-circuit-board platform over a distance of 1mm between the transmitter and the receiver antennas, the received signal amplitude was 650mV with a signal-to-noise ratio (SNR) of 12.5. Based on these results, this should be reduced to a received signal amplitude of 274mV with an SNR of 5.4 on the silicon (SPIDER) platform, which is satisfactory for reliable system operation. It should be noted that the amount of the deliverable power to the external resonator/antenna is physically programmable on the chip, allowing a trade-off between the signal amplitude and SNR on one hand and the consumed power on the other.

The Neural Processing Unit (NPU)

The NPU was tested and characterized from the threshold coverage viewpoint. As shown in Fig. 9, for a certain threshold offset, the positive and negative threshold levels, $V_{TH,P}$ and $V_{TH,N}$, can each cover a range of 500mV, which is much more than the foreseeable voltage offsets for the bandpass preamplifiers and the spike detection comparators.

The operation of the NPU was also tested at high clock rate to examine its capability in reporting the width of the detected spikes. Nominal clock frequency for the NPU is 2MHz. First, the clock frequency was lowered to 100kHz to more easily show how a couple of detected spikes are carried by data packets (Fig. 10). Then, the clock frequency was chosen to be 1MHz since the Labview interface program is not fast enough for 2MHz. As shown in Fig. 11, even at 1MHz the channel scan rate is so fast that each channel is sampled multiple times during the presence of the spike. Thus, the system is also capable of reporting the durations of the spikes in addition to their occurrences. In these tests, pre-recorded neural data was applied to only one channel; the other channels were grounded.



Fig. 8: An outgoing data packet passing through the reverse telemetry back-end



Fig. 9: Threshold coverage



Fig. 10: Assembling data packets to carry the information of the detected spikes, f_{Clock} =100kHz



Fig. 11: Reporting spike widths in the Scan Mode, $f_{Clock} = 1$ MHz.

3. Microsystem Packaging and Implant Procedures

Before the latest MINI design was implanted in a monkey in Pittsburgh, it was thoroughly tested for leakage. The machined housing (Fig. 12) was sent to the University of Pittsburgh, where it was implanted in a life-size replica of a monkey cranium. The fake skull was used so that an accurate representation of how the implant fits on the head could be visualized. Since it mimicked an actual surgery, it was also a forced check that all the appropriate tools and equipment were at hand for the real surgery. For example, it ensured that the correct trephine and screws were being used.



Procedure:

After a craniotomy was created, a thin ring of Kwik-Sil silicone elastomer was extruded around the opening. The cranial implant was placed in this corresponding hole. While the elastomer set, the flexible flanges were molded down around the skull and fixed in place with stainless steel bone screws. The housing implant was then secured to the cranial implant with bone screws. The two o-rings around the circuit board, the circuit board, and the acrylic lid were then placed in the housing. The rest of the skull was filled with water. The acrylic lid was attached and secured in place with four nuts. The lumen area was filled thought through the hypodermic ports. Plastic tubing connected a fluid filled syringe to the port. One port was left open allowing the air from the lumen to escape. If there were no obvious leaks at that point, the port for air release was capped and more fluid was injected to see if the pressure would cause a leak. This simulates the rise in intracranial pressure that occurs after the monkey wakes up from anesthesia.

Discussion:

When the plain circuit board was used there were no leaks. However, when the epoxied circuit board was used, there was a major leak between the circuit board and the lid. Unfortunately, the minor bumps and ridges that formed from the hand application of the epoxy onto the board prevented an even seal. This was large enough for fluid leakage. Another component equally important to the seal are the bubbles that form inside the orings during their fabrication. Large bubbles are a particular problem since the air inside compresses differently than the rest of the silicone elasomer, preventing an even seal. There was no evidence of leakage between the housing and the underside of the circuit

board, independent of board type. It was also noted that the housing secured to the implant very easily.

Overall the results of the tests showed that there was sufficient sealing between the skull and the cranial implant, between the cranial implant and the housing, and between the housing and the circuit board. With minor adjustments to the application procedure, and with an o-ring without any large air bubbles, the assembly should provide a good seal.

MINI-8.0

The only change from the previous design (MINI 7.1) was to the housing implant walls. The housing walls, originally designed to be 0.415" deep, were significantly reduced to only 0.05" in MINI 8.0. This depth still encloses the o-ring between the housing and the bottom of the circuit board along with the circuit board itself. The reduction in the wall height offers better a better view of the connectors while attaching the cables for recordings. The lid now extends down over the housing implant part, and additionally covers and protects the fluid port tubes. The MINI 8.0 design is shown below in Fig. 12. The total height of the housing implant and the cranial implant assembly is only 3/8" tall. The flanges are flexible enough to be molded over the skull and secured in place without and fractures or cracking. The array of bone screw holes permits flexibility in the placement of bone screws. The flexibility of the flanges also gives much easier access to the set screws for securing the housing implant to the cranial implant. In all, the design reduces the number of tools needed for the surgery by at least one, and should quicken the speed of the implant significantly.

Design Modifications from MINI-7.1 to MINI-8.0 (Fig. 13)



Fig. 13: Old and new versions of the MINI design. Left: MINI 7.1; Right: MINI 8.0

Housing walls

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Fig. 14: Side view of MINI 8.0. The total height of the housing and cranial implant assembly is $\sim 3/8^{\circ}$.

cables for recordings. The total height of the assembled housing and cranial implant parts is now only 3/8" tall (Fig. 14).

Lid walls

To account for the shortening of the lid walls, the wall height of the lid had to be extended to cover the connectors. The walls also extend all the way down to the bottom surface of the housing implant.

Fluid port hard cover

The lid also has an additional quarter inch extended pocket opposite to the attachment fixture that covers and protects the fluid ports.

Fluid port sealing plug

In previous implants, the fluid ports were sealed with small amounts of bone wax. At times these bits would get wedged into the lumen area. A series of port covers using a known biocompatible material — NuSil (Nusil: silicone technologies, MED2-4220) — were made. This was done by filling the fluid port cover area of an inverted lid-housing assembly with Nusil. The surface of the fluid port cover area of the inverted lid was pre-coated with dental acrylic providing a buffer region so that when using only the Nusil Cap, it will easily be covered by the fluid port cover area on the lid without any (or minimal) finagling. The silicone elastomeric properties of the NUSIL provide a good seal that should hinder the fluid flow.

Lid Lip

In order to stabilize and balance the lid, an internal lip was designed into the lid such that it will rest on the wall of the housing implant. This lip adds significant protection against damage caused by any torsional or bending stresses. It also assists in alignment when placing the lid on the housing.

Next Iteration:

In the next iteration the lid will be machined out of polypropylene, reducing the weight of the capped device. The lid, now bearing the majority of the material, can be machined out of any non-corrosive non-porous material (generally a polymer such as polypropylene) since it does not have any contact with the tissue. This greatly reduces the weight of the overall device and the length of time it takes to machine. Stock polypropylene is extremely low cost and has a very smooth surface, which reduces the possibility of bacterial build up. It is non-toxic and is chemical resistant. It is a hard material and is almost five times lighter than titanium.

We will have a different method of applying the epoxy that will reduce the variance in the thickness of the epoxy. A resolution will be made as to how to approach producing high-quality and high-yield rectangular o-rings after inspection of different methods, materials, and a cost analysis of outsourcing the o-rings to a company.

4. Conclusions

During the past quarter, work has moved forward on the design of the electrode interface electronics for the cortical microsystem, on the testing of the wireless interface,

and on the implant housings. The recording amplifiers have been redesigned to make them programmable in terms of their gains, offsets, and low-frequency cutoffs. Gain is programmable between 100 and 1000, and both offset and cutoff frequency are set using on-chip 12b analog-to-digital converters. These ADCs resolve 0.7mV in setting these parameters. Sixty-four amplifiers have been integrated on a single 3.1mm x 4.8mm chip that dissipates only 3.2mW. This new amplifier chip replaces four of our earlier 16-channel chips and offers increased flexibility. The chip is in fabrication now in a commercial foundry and will be returned for testing later this month.

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