HermesC: RF Wireless Low-Power Neural Recording System for Freely Behaving Primates

Cynthia A. Chestek
Vikash Gilja
Paul Nuyujukian
Stephen I. Ryu
Krishna V. Shenoy
Stanford University
Stanford, CA 94305
cindyc@stanford.edu

Ryan J. Kier
Florian Solzbacher
Reid R. Harrison
University of Utah
Salt Lake City, UT 84112

Abstract— **Neural prosthetics for motor systems is a rapidly growing field with the potential to provide treatment for amputees or patients suffering from neurological injury and disease. To determine whether a physically active patient such as an amputee can take advantage of these systems, we seek to develop an animal model of freely moving humans. Therefore, we have developed and tested HermesC, a system for recording neural activity from electrode arrays implanted in rhesus monkeys and transmitting this data wirelessly. This system is based on the integrated neural interface (INI) microchip, which amplifies, digitizes, and transmits neural data across a ~900 MHz wireless channel. The wireless transmission has a range of ~4 m in free space. All together, this device consumes 11.7 mA from a 4.0 V lithium ion battery pack for a total of 46.8 mW. To test the performance, the device was used to record and telemeter one channel of broadband neural data at 15.7 kSps from one monkey doing various physical activities in a home cage, such as eating, climbing and swinging. The in-band noise of the recorded neural signal is 34 µVrms, which is low enough to allow the detection of neural units on an active electrode. This system can be readily upgraded to use future generations of the INI chip, with circuits providing 96 channels of programmable threshold crossing event data.**

I. INTRODUCTION

Cortically-controlled neural prostheses extract signals from the central nervous system in order to drive prosthetic devices such as limbs and computer cursors [1-4]. However, at least one major obstacle appears to stand in the way of clinical adoption. Advancements have occurred in highly controlled settings with immobile animals or humans. Also, highly reduced visual workspaces and eye fixation was often used. In a human clinical setting, particularly for active amputees, these are not realistic constraints. Therefore, the next challenge for neural prosthetic systems is to release these constraints, and attempt to replicate previous high performance results in this more practical, yet neurally complex setting.

This requires an animal model of freely moving humans. Rhesus macaque monkeys are appropriate subjects, since they can make the coordinated arm movements that one would like to decode. Also, there is a large body of neuroscience and neural prosthetics research in macaques. Several systems have been developed to record neural data during free movement. Two systems record data to onboard memory, which can be subsequently downloaded [5,6]. It would be difficult to scale these systems up substantially since memory can fill rather quickly with multi-channel data. Several systems use off the shelf electronics to transmit neural data wirelessly [7,8]. However, these telemetry systems have relatively high power consumption, running for 6-8 hours before requiring a new battery. We would like to record for many days without servicing the device with an approach that can be readily scaled to 96 channels. To that end, we have developed HermesC, a wireless system for recording neural data from freely moving primates. This system uses the Integrated Neural Interface (INI) microchip, which is part of a larger project to develop a fully implantable 96-channel system [9]. Other systems have been developed that could potentially provide similar functionality, but to our knowledge have not been demonstrated with freely behaving primates [10-13].

HermesC samples one channel of 10-bit neural data from a CKI 96-channel array at 15.7 kSps and transmits those data wirelessly at ~920 MHz to a receiver outside of the cage. This device has been used to record data from a rhesus macaque performing many unconstrained regular activities.

II. METHODS

Figure 1 shows a diagram of the design. It consists of a neural connector, a PCB with a custom microchip to record, digitize, and transmit the data, and an external receiver.

A. Physical Design

Neural data are obtained through a 96-channel cortical array attached to a zero-insertion-force connector on the skull

978-1-4244-1684-4/08/$25.00 ©2008 IEEE

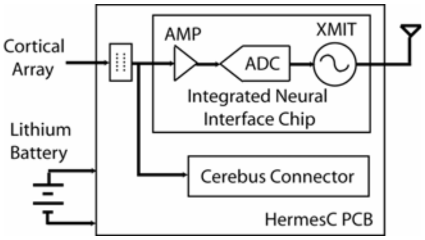

Figure 1. Design Overview

(Cyberkinetics Neurotechnology Systems Inc.). Three different custom head-stages provide access to 3 banks of 32 channels with connectors that attach directly to the PCB. The entire system, which includes the skull connector, the PCB, and a lithium battery pack, is housed in an aluminum enclosure attached to the skull with titanium hardware and methyl methacrylate. The mechanical setup is identical to the HermesB system [5], except that a stub antenna protrudes 8 mm through a hole in the lid (Fig 2B). This antenna is immobilized and sealed with epoxy. A rubber gasket between the lid and the enclosure provides a watertight seal around the edges. The total size of the enclosure is 60x70x45 mm.

B. Electronics

The electronics for HermesC consist primarily of the INI3 chip, which is described in detail in [14]. Briefly, it consists of three stages: The bioamplifier stage amplifies the signal by 1000 and band-pass filters the neural data between < 1 Hz and 4.5 kHz. The data then pass to a 10-bit analog to digital converter (ADC) at a rate of 15.7 kSps for one channel. The digital data are processed by the RF transmitter stage, which outputs the signal to an antenna. The center frequency is programmable between 880 MHz and 980 MHz using frequency shift keying (FSK) with a programmable spacing of 165-660 kHz. Data are transmitted in 16-sample frames at 345.6 kbps with one parity bit computed for each 10-bit ADC sample. The additional transmit bandwidth beyond 172.7 kbps is reserved for threshold crossing data, an INI feature not currently exploited by the HermesC system. The device can be programmed and powered wirelessly through an inductive link to an attached coil; in this study, however, a wired connection was used for simplicity. After device programming, this connection could simply be removed for the rest of the experiment. While the INI chip usually consumes < 10 mW, an extra power amplifier stage within the chip was used to increase the transmission range. Overall, HermesC consumes 11.7 mA at 4.0 V, for a total of 46.8 mW. The INI chip itself can run on a voltage source between 3-4 V. The PCB is shown in Figure 2C. Since the chip is not receiving a wireless clock and power signal in this context, the PCB includes a 3.3V voltage regulator, fuses, and a clock oscillator. It also includes various connectors and test points for accessing the chip.

The chip includes 96 separate amplifiers and was developed for a fully implantable system [9], in which it could be bonded directly on the back of the 96-channel electrode array. HermesC represents a test platform for this system, in which signals can be easily accessed, and the external circuitry can be rapidly reconfigured. For this context, the INI chip was packaged in a 64-pin low profile quad flat package (LQFP). While currently, only one channel is transmitted using the ADC, the PCB includes the future capability to access 20 electrodes simultaneously and transmit threshold crossings from these channels using the next revision of the INI chip. The current power consumption includes wireless transmission of all 96 channels of threshold crossings. The PCB also provides an alternate data path to a traditional head-stage connector for a commercial neural recording system, Cerebus (CKI). In this way, data can be obtained simultaneously and then compared.

Compared to HermesB which consumed 71 mA from its 1120 mA-hr battery pack for 16 hrs of operation, HermesC can run continuously for 4.4 days as it requires only 11.7 mA. Furthermore, the HermesC system requires only one circuit board within the protected enclosure, which should make it possible to add a second battery and double the recording time. Since the data are wirelessly transmitted rather than spooled to compact flash, neural data can be easily synchronized with video behavioral data (Fig 2D).

Data were collected with a commercial FSK transceiver, the ADF7025 development board (Analog Devices), receiving in the 902-928 MHz range. The receiver was connected to a half-wave whip antenna and was powered and controlled by a USB-6259 DAQ (National Instruments). Neural data were collected on a laptop and analyzed using MATLAB.

C. Experimental Setup

On 13 occasions this system was tested with a freely

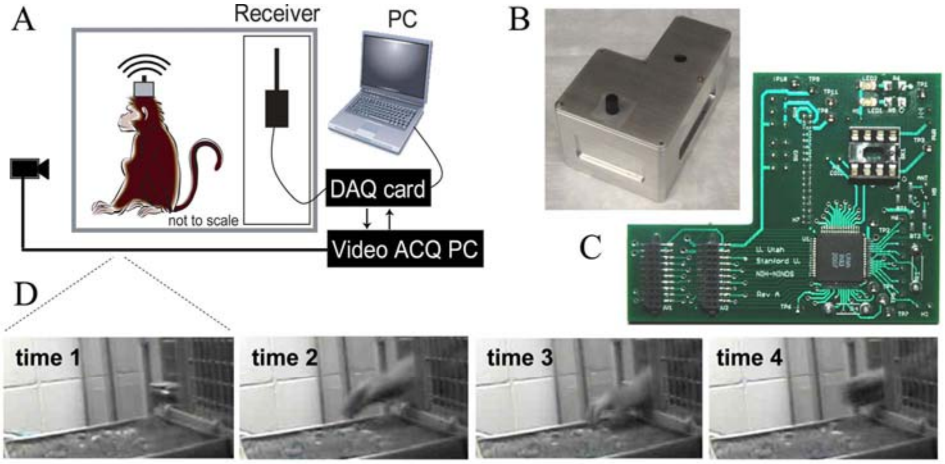

Figure 2. HermesC System (A) Setup with animal in a metal home cage and receiving antenna on plastic cage window (B) Aluminum enclosure with stub antenna in lid (C) PCB with INI chip (D) Example video data

moving primate. One 6.9 kg rhesus macaque, was implanted with a 96-electrode array using standard neurosurgical techniques two years prior to the current study. This array continues to provide many large neural units. The HermesC PCB was placed inside the aluminum enclosure on the head while the animal was seated in a primate chair. With the lid removed, the device was programmed using a wired connection. The device was programmed to transmit data at a center frequency of 919 MHz with an FSK frequency spacing of 460 kHz. The lid with the protruding stub antenna was replaced, and the animal was returned to the home cage.

The receiver was placed outside the animal's home cage with the antenna attached to a plastic window on the cage's side-wall, as shown in Figure 2A. The transmit frequency was measured within 50 kHz using a portable spectrum analyzer (Protek, 3290N). Data were recorded on a laptop. General notes on the animal's behavior were taken during recording or a video camera was used.

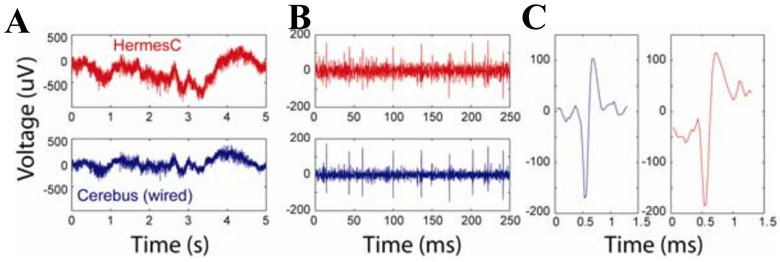

Figure 3. Comparison of neural recordings from HermesC, Cerebus (A) Unfiltered raw data from HermesC (red) and Cerebus (blue) (B) Spike train high pass filtered at 250 Hz from both (C) Individual action potentials, unfiltered from both

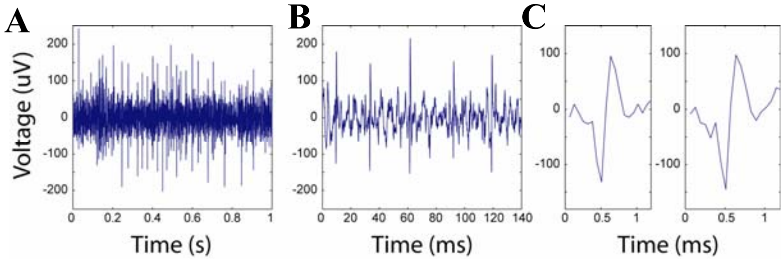

Figure 4. Neural data from monkey freely moving in a home cage (A,B) Data highpass filtered at 250 Hz at different time bases (C) Two examples of individual action potentials, unfiltered

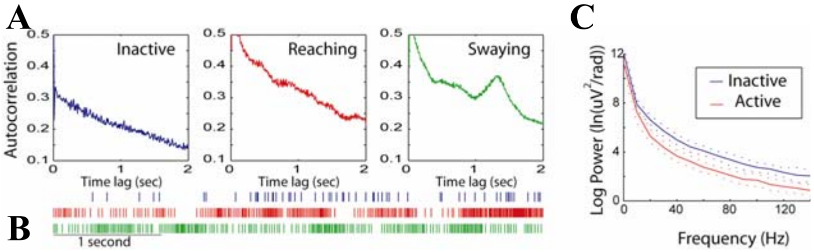

Figure 5. Neural activity during various activities in the cage (A) Autocorrelation of spike rasters convolved with a gaussian window (B) Example spike rasters for each behavior (color coded) (C) Comparison of LFP during active/inactive periods. Dotted line denotes standard deviation

III. RESULTS

A. Device Validation

To validate the neural data collection before freely moving experiments, we recorded simultaneously from the wireless link, as well as a wired neural data acquisition system, Cerebus, while in a neuroscience rig. A channel with a relatively large neural unit was chosen. Neural data were recorded from both during a 2 minute period, and aligned precisely by hand. Figure 3A shows a 5 second snippet of raw data in which the data from the commercial system (bottom) correspond with the data recorded with HermesC. Similarly, Figure 3B shows a spike train created by high-pass filtering the raw broadband data from both devices at 250 Hz. Figure 3C shows one action potential, unfiltered, from both. The in-band noise is somewhat higher for HermesC, at 27.4 µVrms compared to 17.4 µVrms in the commercial Cerebus system from the same electrode inside of the shielded rig.

To exercise the wireless link prior to use with the animal, the circuitry was tested in an unimplanted aluminum enclosure with the same lid and stub antenna, shown in Figure 2B. The device was programmed to transmit at 918 MHz and data were received at various distances with the receiving half-wave whip antenna in three different orientations. In the preferred orientation, the estimated bit error rate (BER) stayed below 10^{-5} up to 5 m away. In both of the two non-optimal orientations, the BER stayed below 10^{-5} up to 3.5 m away. The device was also tested inside a 105 cm x 87 cm x 91 cm metal cage with walls composed of a 1" pitch wire grid. The receiving antenna was placed at the top of a plastic window on the cage wall. The device was placed in 3 points along each of 3 directions and 3 heights, for a total of 27 positions within the cage. The BER remained below 10^{-5} for all locations. To maintain this low error rate when the device was moving with respect to the metal, a 6 dB attenuator was added to the transmitter output to reduce small frequency shifts that resulted from small antenna impedance changes. The INI chip does not contain a PLL due to power constraints.

B. Neural Data from a Freely Moving Primate

To demonstrate the functionality of this system in a freely moving primate, neural data were recorded wirelessly from a monkey while she was in her home cage. Figure 4 shows neural data at three different time scales. This particular set of spikes was taken from a trial in which the animal was actively swaying back and forth in the cage. Neural data are high-pass filtered at 250 Hz to reveal the spiking activity. The in-band noise level is 34.5 µVrms with action potentials of 230 µVpp.

With the freely behaving animal, a small amount of data was lost due to RF transmission errors. These errors can be mitigated by detecting incomplete frame headers and removing that entire frame, and also by removing words with incorrect parity bits. Using this approach, 0.2% of the data on average were lost during extended recording. One likely cause for the errors is large changes in antenna impedance when the device is touching the metal cage wall. To compensate, multiple receivers could be used to cover more physical space and a larger transmission bandwidth. However, using the current setup, both the noise and BER were sufficiently low to reliably record action potentials from active electrodes.

To demonstrate the experimental capabilities of this device, even recording from one neuron at a time it is possible to identify correlations between patterns of neural activity and certain common behaviors. Figure 5B shows examples of raster plots of neural activity along with autocorrelation functions during inactivity, reaching (non-rhythmic bursts) and swaying (rhythmic bursts) in Figure 5A. Mean firing rates during those activities were 31.8 ± 29.2 Hz, 53.5 ± 43.0 Hz, and 46.3 ± 26.6 Hz respectively (mean ± std). Figure 5C shows a power spectrum for LFP during active versus inactive periods. The dotted line denotes the standard deviation, which suggests that these states could be accurately decoded using LFP only. With more neural channels and more quantified behaviors, it may be possible to more accurately decode the animal's behavioral state from the neural activity alone.

IV. DISCUSSION

Currently, HermesC, equipped with the INI chip, has the capability to wirelessly transmit one channel of broadband 10-bit neural data from a freely moving primate. With the next generation of the INI microchip, this system will be capable of broadcasting threshold crossings on 20 electrodes without further modifications or increased power consumption, in addition to one broadband channel. Additional development is underway to accommodate the very large volume of data that this system will produce for long-term studies, since the INI data stream produces 345.6 kbps, or approximately 3.6 GB / day and the video stream creates an additional ~80 GB / day.

This system enables new studies in both neural prosthetics and systems neuroscience. For prosthetics, several important experiments can now be conducted. First, neural prosthetic algorithms can be tested in a far less constrained environment. With an animal model of a freely moving human, results will be more applicable to human amputees. Second, most prosthetic experiments use a structured trial where the animal is told when to start and stop, and decoding algorithms take advantage of that information, which will not be available in clinical systems. With Hermes C, it may also be possible to decode the general context of an activity, for example eating, and use this to help determine what kind of movements the animal intends to make. Moving towards human devices, it provides a good test bed for a planned fully implantable version of a 96-electrode wireless system [9], which may have important implications for clinical neural prosthetics.

In systems neuroscience, the understanding of visual processing was transformed a decade ago when vision neuroscientists began recording from behaving animals without eye fixation and with naturalistic scenes, and found that neurons respond differently in this more natural visual context. HermesC may help make it possible to move beyond the technological confines that currently restrict the study of motor processing to animals seated in chairs and interacting with simplistic environments. If successful, such studies will dramatically advance our understanding of cortical motor control across a much wider range of motor contexts.

ACKNOWLEDGMENT

We thank Mackenzie Risch for expert surgical assistance and veterinary care, Afsheen Afshar, Gopal Santhanam, and Drew Haven for technical consultation, and Sandy Eisensee for administrative support. This study was supported by the NSF Graduate Research Fellowships (C.A.C., V.G.), William R Hewlett Stanford Graduate Fellowship (C.A.C.), NDSEG Fellowship (V.G.), Stanford Medical Scholars Program (P. N.), NSF CAREER award ECS-0134336 (R.H.) and the following awards to K.V.S.: Burroughs Wellcome Fund Career Award in the Biomedical Sciences, The Christopher Reeve Paralysis Foundation, Stanford Center for Integrated Systems, the NSF Center for Neuromorphic Systems Engineering at Caltech, the ONR, the Sloan Foundation, the Whitaker Foundation and NIH-NINDS (N01-NS-4-2362).

REFERENCES

[1] A. B. Schwartz, X. T. Cui, D. J. Weber, and D. W. Moran "Brain-controlled interfaces: movement restoration with neural prosthetics," Neuron, vol. 52, pp. 205-220, Oct 5 2006.

[2] D. M. Taylor, S. I. Tillery, and A. B. Schwartz, "Direct cortical control of 3D neuroprosthetic devices," Science, vol. 296, pp. 1829-32, 2002.

[3] G. Santhanam, S. I. Ryu, B. M. Yu, A. Afshar, and K. V. Shenoy, "A high-performance brain-computer interface," Nature, vol. 442, pp. 195-8, Jul 13 2006.

[4] L. R. Hochberg et al, "Neural ensemble control of prosthetic devices by a human with tetraplegia," Nature, vol. 442, pp. 164-71, Jul 13 2006.

[5] G. Sanathanam et al, "HermesB: A continuous neural recording system for freely behaving primates," IEEE Trans. in Biomedical Eng., vol. 54, pp. 2037-50, 2007.

[6] J. Mavoori, A. Jackson, C. Diorio, and E. E. Fetz, "An autonomous implantable computer for neural recording and stimulation in unrestrained primates," J. of Neurosci .Methods, vol. 148, pp. 71-7, 15 Oct 2005.

[7] U. Jurgens and S. R. Hage, "Telemetric recordings of neuronal activity," Methods, vol. 38, pp. 195-201, 2006.

[8] N. L. Sun et al, "Neurophysiological recordings in freely moving monkeys," Methods, vol. 38, pp. 202-209, 2006.

[9] R. R. Harrison et al, "A low-power integrated circuit for a wireless 100-electrode neural recording system," IEEE J. of Solid State Circuits, vol. 42, pp. 123-133, 2007.

[10] M. Mojarradi et al, "A Miniaturized neuroprosthesis suitable for implantation into the brain," IEEE Trans Neur Sys Rehab Eng, vol. 11, pp. 38-42, 2003.

[11] P. Mohseni, K. Najafi, S. J. Eliades, and X. Wang, "Wireless multichannel biopotential recoding using an integrated FM telemetry circuit," IEEE Trans Neur Sys Rehab Eng, vol. 13, pp. 263-71, 2005.

[12] A. M. Sodagar, K. D. Wise, and K. Najafi, "A fully integrated mixed-signal neural processor for implantable multichannel cortical recording," IEEE Trans Biomed Eng, vol. 54, pp. 1075-88, 2007.

[13] M. Rizk, I. Obeid, S. H. Callender, and P. D. Wolf, "A single-chip signal processing and telemetry engine for an implantable 96-channel neural data acquisition system," J Neural Eng, vol. 4, pp. 309-21, 2007.

[14] R. R. Harrison et al, "Wireless neural signal acquisition with single low-power integrated circuit," to appear in IEEE Intl Symposium on Circuits and Systems (ISCAS 2008), Seattle, WA, 2008.