Project Proposal: Analyzing Feasibility of Neural Dust Mote Technology for Successful Transmission of Neural Signals

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Abstract: Brain-machine interfacing is an exciting field with a broad range of applications in neuroprosthetics. A major drawback to existing systems is the lack of a tetherless interface that is viable for the lifetime of the user. The design of a wireless system made up of thousands of ultrasonic powered small scale (10-100µm) implantable sensor motes is proposed as a path towards a truly chronic brain-machine interface in two papers, "Neural Dust: An Ultrasonic, Low Power Solution for Chronic Brain-Machine Interface," and "Model Validation of Untethered, Ultrasonic Neural Dust Motes for Cortical Recording," by Donjin Seo et. al. We attempt to understand the design of this system and its delicate balance between power and signal propagation constraints within the neural tissue.

Introduction and Motivation: In order to improve our understanding of what is happening inside the human brain, scientists, doctors and engineers have been trying to devise methods of extracting physiological information from brain tissue for several decades. Electroencephalographic (EEG) signals, collected by electrodes placed on the scalp, were precursors to the idea that electrical activity could be monitored from leads placed under the skull and directly on the cortical tissue for more accurate readings [1]. However, the tradeoff with this design for more accurate monitoring of brain tissue activity is that a non-invasive approach is no longer an option. Researchers can attempt to use a wired configuration that protrudes out of the skull and connects to an external receiver, or attempt a wireless solution that sends signals through the skull, neither of which are trivial undertakings. Clinicians implanting devices need to be concerned with biocompatibility of their systems, while researchers focusing on processing the collected signals are faced with noise issues arising from the body's sub-optimal properties as a transmission medium [2]. Due to the far-reaching appeal that the ability to closely monitor the electrical activity of human cortical tissue has in the scientific community, there have been a variety of attempts to overcome these inherent challenges. There have been successful attempts to implant recording systems in the test subject's skull which were capable of sending between 10s and 100s of channels of data [5]. Additionally, these neural implants were viable on the range of months to a few years [5]. In order to develop more robust monitoring systems, there is still plenty of room for innovation.

Problem Statement: In order to effectively communicate brain activity with small scale sensor motes, the key tradeoffs that must be examined are the power requirement of the system and signal attenuation in cortical tissue, in relation to mote size. In order to lengthen the lifetime of neural implants so as to reduce the amount of surgical procedures a subject must undergo, it is critical to minimize sensor mote size. However, a reduction in mote size requires more power to overcome the noise floor associated with the decreased differential between recording electrodes. In addition, power transfer efficiency is decreased as mote size decreases. If power is too low, the signal attenuation within the tissue will prevent accurate readings from being obtained. It is therefore an optimization problem between mote size, power, and signal attenuation that is the essential problem to investigate. Our study will focus on the theoretical background presented "Neural Dust: An Ultrasonic, Low Power Solution for Chronic Brain-Machine Interface," as well as the practical application in "Model Validation of Untethered, Ultrasonic Neural Dust Motes for Cortical Recording," both by Donjin Seo et. al., to understand the balance between power and attenuation in relation to mote size in chronic neural interfaces. One of the mathematical formulas we will look to understand, which determines backscatter sensitivity, is as follows: $S = V_{neural}/(I_{DS} + (V_{DS}/2R_b))*(\partial I_{DS})/\partial V_{GS}) = V_{neural}*(gm/(I_{DS} + (V_{DS}/2R_b))$

Where V_{neural} is the voltage produced by an active neuron and I_{DS}, V_{GS}, and R_b are characteristics of the mote architecture.

Additional research is necessary to understand the how the power transfer efficiency was calculated for different mote sizes.

Goals: We would like to better understand how the ultrasound-based communication system proposed in the two papers above contrasts previous neural interface systems that relied on electromagnetic waves for signal transduction. Furthermore, we would like to reproduce the mathematical models in the papers that compute the power efficiency and signal attenuation for nodes of different sizes, and be able to directly compare these values to those that have been achieved when using EM-based interfaces.

Team organization: Patrick will focus on the power relationship, especially in regard to different mote sizes, and Kyle will be concerned primarily with the signal attenuation concerns in the neural medium. We will plan to split the work evenly on the various tasks (written report, simulation, and presentation), but may break the work up in more specific detail as we get closer to the deadline.

References:

[1] J. J. Vidal, "Towards Direct Brain-Computer Communication," Annual Reviews of Biophysics and Bioengineering, vol. 2, pp. 157-180, 1973.

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[3] D. Seo et. al., "Neural Dust: An Ultrasonic, Low Power Solution for Chronic Brain-Machine Interface," Quantitative Biology, 2013.

[4] D. Seo et. al., "Model Validation of Untethered, Ultrasonic Neural Dust Motes for Cortical Recording," Journal of Neuroscience Methods, vol. 244, pp. 114-122, 2015.

[5] Alivisatos AP, et al. (2013) The Brain Activity Map. Science 339:1284-5.