Microcircuit Design for Real-Time Data Acquisition and Neuromuscular Control of Insect Motion

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Abstract

The reliable control of the motion of insects by electronic hardware would allow for the construction of advanced cyborg insects that would overcome current technological limitations that plague today's micro robots. This paper discusses a concept for an accessible device that would enable such control. The microcircuit enables real-time data acquisition and multi-channel stimulation that can be used for modeling and control of insect neurodynamics.

Keywords: neuro-engineering, brain-machine interface

Introduction

Since the early 2000s, research teams around the world have been working towards producing hardware and a methodology for tethering live insects to equipment that would allow them to control the movement of these insects. Each paper in the field seeks to solve a similar problem: at the scale of insects, current technologies for power storage in the form of batteries, and power delivery in the form of actuators, are insufficient at best (Sato & Maharbiz, 2010). Using an insect as a mobile platform for electronic hardware allows us to overcome these shortcomings of our current robotic technology.

Many papers seek to improve our knowledge of how to interface with insects in a way that is minimally invasive but maximally effective. In this way, the insect's innate control systems are capable of maintaining the insect's health and the low level tasks such as muscle coordination, while the researchers are able to direct its movement with a control system "wrapped" around the control systems present in the insect itself (Sato, 2009).

When it comes to development of this hardware, however, the same issues that hinder insect scale robots continue to plague todays designs for cyborgs or biobots. That is, for long battery life and for long distance communication and controllability of the insect, current technology is not compact enough to be carried by even the strongest of insects (Kuwana, Shimoyama, & Miura, n.d.); (Sato & Maharbiz, 2010). Instead, a compromise must be made between these and other parameters that are important to the overall capability of a biobot.

Some researchers have specifically investigated the implementation of communication with the insects nervous system hoping to find a stimulation profile that results in reliable control of the insect (Erickson, Herrera, Bustamante, Shingiro, & Bowen, 2015). These contributions discuss parameters that best promote a consistent response from the insect receiving the stimulus. Electrical interfaces with insects are always one of three types: direct interfaces with neural tissue in the brain, with muscle tissue, or most commonly with nerves in a nerve cord (*e.g.* antennae). The potential for more advanced control by implementing direct stimulation of the brain or even external visual stimulus has been discussed and hypothesized, but rarely successfully realized (Sato et al., 2008)(Sato & Maharbiz, 2010).

Multiple different teams of researchers have published information on methods they have developed for control of insect motion in various modes across various species of beetles, cockroaches, and moths. The most basic control discussed is the initiation and cessation of flight or walking (Sato et al., 2010); (Latif & Bozkurt, 2012). Slightly more advanced is the directional control of the motion. This was achieved in one of two ways: muscular stimulation that resulted in asymmetry in the contraction of the muscles, (Sato, Peeri, Baghoomian, Berry, & Maharbiz, 2009) or stimulation of antennae (Latif & Bozkurt, 2012); (Bozkurt, Lal, & Gilmour, 2009).

Despite the prior work, there remains a lot to be done before real world implementation of cyborg insects is viable. With success rates in the literature of no higher than 50% (Latif & Bozkurt, 2012); (Erickson et al., 2015), it is apparent that a more advanced scheme for control of these insects is in order if they are ever to be considered a viable platform to take over for conventional robots on a small scale.

Here, we explore the design and implementation of a device that is intended to improve on the capability of other biorobotic insect platforms. Using a platform with more channels for stimulation provides greater freedom and flexibility for stimulation, control, and measurement. Our hardware design incorporates a 9 axis inertial measurement unit that provides linear and rotational acceleration measurements, as well as compass and temperature data. Acceleration and heading data should allow us to extrapolate the trajectory of the insect, and ambient temperature has been found to have an important impact on the performance of certain insect hosts (Latif & Bozkurt, 2012). The implementation of such a circuit should also allow for model-based feedback control of the insect's trajectory. Next, we present the hardware design, followed by results obtained by the platform and discussions of the data.

Hardware Design

Discussed in the following subsections are the rationales for the choices made in the hardware design. The common design features among the examples presented in the literature are a lightweight battery, multiple channels for exploring and array of effective areas for stimulation, and wireless capability to eliminate tethers that interfere with the movement of the insect. When fully assembled, devices that have been successfully carried by insects were usually less than 3 grams, with battery life in an operating mode of approximately 30 minutes (Sato & Maharbiz, 2010). The implementation of low power electronics is paramount to the successful implementation of cyborg insects in any real world application, and it remains a challenge despite the development of increasingly efficient technologies (Sato & Maharbiz, 2010). The aim is to develop a platform with similar physical specifications as examples in the literature that expands on the standard feature set.

Microcontroller: Texas Instruments TI CC2431 microcontrollers were a popular choice among researchers for their cyborg microcontrollers. They are available in small, light form factors, and researchers who used them frequently ended up with circuits weighing around 500mg (Sato & Maharbiz, 2010); (Sato et al., 2009). Many modern microcontrollers include integrated radio capability and low power. Microcontroller technology is constantly improving, so most modern microcontrollers with the proper feature set should be decent candidates for our design in terms of form factor, efficiency, and power. Therefore, the low power, Bluetooth Low Energy enabled Atmel SAMB11-ZR microcontroller was chosen in the initial hardware design for its power characteristics, small form factor, and integrated antenna.

Battery: Every wireless hardware platform described in the literature is powered by a battery. The most common choice is a lithium polymer cell which produces 3.7V nominally (Sato et al., 2009); (Latif & Bozkurt, 2012); (Cao & Sato, 2017). Sato (2009) used a micro battery for a cochlear implant, for example. The longest lasting controller discussed had a flight time of 30 minutes and was able to run for up to 24 hours in sleep mode. So the first iteration of our new hardware utilizes a standard coin cell lithium battery, which should give good performance. Future iterations, however, may explore solar charging of a supercapacitor or battery to improve the battery life and thus the range of the cyborg insect.

Electrodes: Some of the most important components in the hardware design are the electrodes that act as the interface between the electronics and the tissue of the insect. Many different types of electrodes have been used, but stainless steel and silver electrodes were the most frequently used and discussed (Sato & Maharbiz, 2010); (Cao & Sato, 2017); (Erickson et al., 2015). These electrodes ranged in diameter from 150μm to 200μm for the conductors, usually with Teflon (PTFE) insulation. The creation and implementation of more advanced probing techniques is also possible. Sato describes the method of fabrication of Michigan probes, a complicated process which would require specialized equipment (Sato et al., 2010). Similarly, Bozkurt describes very small probes with multiple channels for stimulation that can be implanted during an insect's pupa stage for later stimulation of the adult (Bozkurt et al., 2007). These electrodes and the steps for implanting them are complicated.

For the purpose of keeping the hardware for this research accessible and relatively inexpensive, we have chosen not to implement the more advanced electrode styles. By using the multi channel stimulation and sensing capability of the hardware, we are able to evaluate the quality of the electrode-tissue interfaces by applying stimulus through one electrode while measuring the signals on the others. Using an equivalent circuit model of the electrode-tissue interface, one can determine if the electrodes are properly implanted and functioning (Latif & Bozkurt, 2012). Since the quality of the stimulus and the data gathered can be guaranteed, we shall implement these simpler electrodes.

Peripherals: Using four of the microcontroller's pulse width modulation enabled GPIO pins, four channel stimulation of the insect is possible. An SPI enabled digital potentiometer is used to adjust the voltage of the stimulation for increased control over the stimulus parameters, while the frequency and duty cycle can be adjusted through the microcontroller. A 9 axis IMU, also using SPI communication, is implemented for the measurement of the insect's 6 degree of freedom motion, as well as its compass heading and the ambient temperature. The hardware interfaces with a computer via Bluetooth, where the stimulation parameters can be set and data can be recorded and processed. The circuit is shown in Figure 1.

In the following section, some of the early data gathered from the movement of a cyborg cockroach is presented and analyzed. As the hardware is finalized, more data will be available for each test, and more conclusions can be drawn.

Preliminary Results and Discussions

A basic two channel stimulation of a cockroach's antenna lobes was performed as a baseline experiment to gather preliminary data about the reaction of the roach to stimulus. Figure 2 shows the PWM signal applied to the antenna lobes to stimulate the roach. The following signal construction parameters were used: 1.2V amplitude, 55Hz frequency, 50% duty cycle. Such a signal was found to be most robust in terms of the response of the roach. A series of 500ms stimuli to the right and left antenna lobes are shown with the resultant trajectory of the roach in Figure 3. The first of the three graphs shows the stimulus of the antennae over time. “Right Stimulus” denotes stimulus of the left antenna lobe, which results in a right turn. Conversely, “Left Stimulus” corresponds to stimulus of the right antenna lobe, resulting in a left turn. Each stimulus, however, resulted in a different response. This is showed in the second graph. For each stimulus shown in the first graph, the response in the form of a turn is shown. A right turn is measured in positive degrees, and a left turn is measured in negative degrees. The third graph shows the cumulative heading of the roach over time. The roach begins

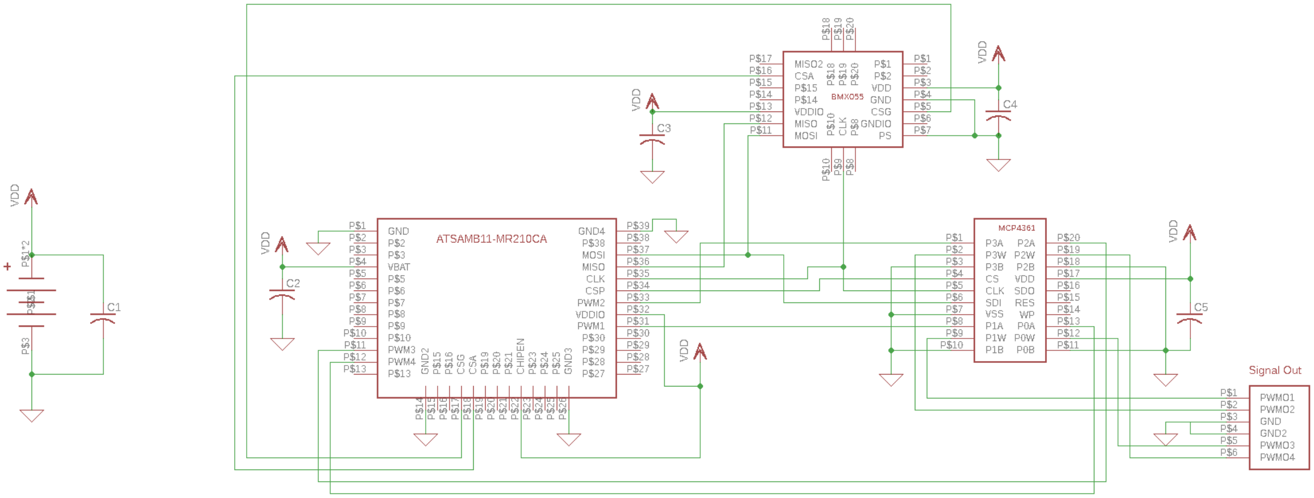

Figure 1: Schematic representation of the proposed circuit design. The Atmel Microcontroller's PWM enabled GPIO pins are connected directly to the inputs of a 4 channel digital potentiometer, which controls the output voltage at the electrode connector, denoted by the "signal out" block. Both the IMU and digital potentiometer are connected to the microcontroller via the SPI bus. Discrete bypass capacitors are included for decoupling the sensitive electronics from a noisy power supply. The importance of minimal design has been weighed against robustness to interference and a variable power supply, and a suitable compromise has been reached. Rapid prototyping and development was carried out using a desktop PCB printer.

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at a heading of 0 degrees (North) each response is added in succession, giving the resultant heading with respect to a fixed North direction over time.

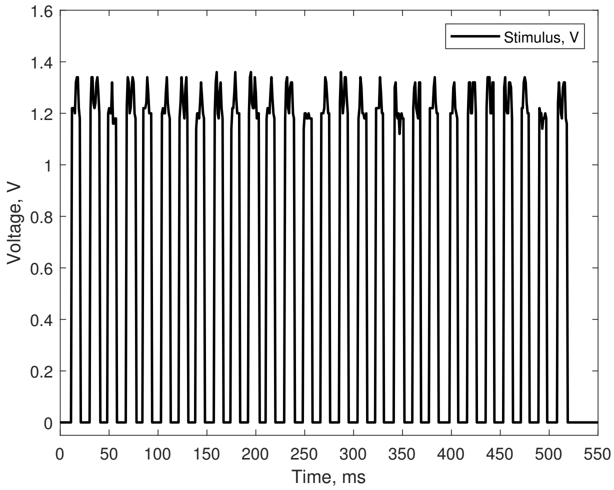

Figure 2: This waveform is an example of the PWM stimulus applied to the antenna lobes. Shown is a 1.2V, 55Hz, 50% duty cycle, 500ms stimulus.

The data shown in Figure 3 reveals an interesting behavior. While the roach responds strongly to initial stimulus in either direction, any subsequent stimulus on the same side yields an exponentially decreasing response.

The microcontroller's PWM channels are used for stimulation of the insect, which enables potential for accurate system identification. It enables the design of a Pseudo-Random-Binary-Sequence (PRBS) current stimulation u, that is rich in frequency content. The response to the PRBS is captured by the microcontroller's IMU sensors that forms the response vector x. A high fidelity dynamical system model $\dot{x}(t) = f(x,u)$ can then be optimized to fit the obtained data corresponding to the neuro-muscular behavior (Ionescu, Dutta, & De Keyser, 2012). A wide array of model-based non-linear control techniques can then be used to automatically generate current stimulus u that steers the insect to a desired trajectory (Dutta, De Keyser, & Nopens, 2012).

Conclusion

The use of insects as platforms for small robots has an incredible number of useful applications. While research has been conducted on the subject for years, there has not been significant progress made towards reliable control of insects. fifty percent success rates are nowhere near sufficient for any search and rescue or defense applications where they seem to be aimed. Work remains to be done in many areas including but not limited to location and parameters for stimulation, sensors and data logging, long range communication, and power efficiency or energy density.

We make a contribution towards the realization of some of these goals by developing hardware that will allow for detailed analysis of the neuro-muscular control of the motion of insects. Our microcircuit enables a more sophisticated system identification and closed loop, model-based control systems

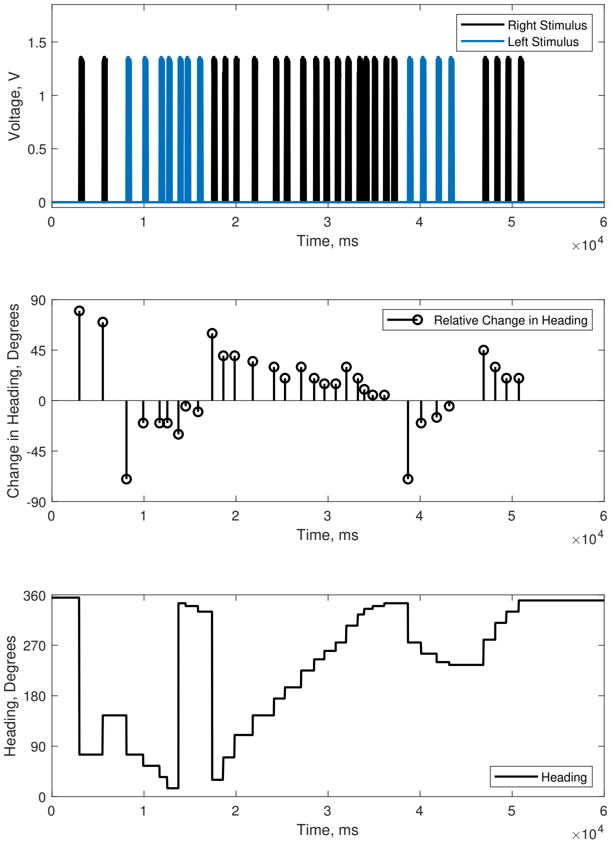

Figure 3: Over the course of a 60 second experiment, multiple left and right stimuli were applied to the antenna lobes of the roach. Each stimulus depicted in the graph has the same parameters shown in Figure 2. A positive change in the heading corresponds to a right turn, while a negative change in heading corresponds to a left turn. The third graph shows the real heading of the roach in the ground frame of reference with respect to time.

will be implemented for the precision maneuvering of insects.

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References

Bozkurt, A., Lal, A., & Gilmour, R. (2009). Radio control of insects for biobotic domestication. *2009 4th International IEEE/EMBS Conference on Neural Engineering*. doi: 10.1109/ner.2009.5109272

Bozkurt, A., Paul, A., Pulla, S., Ramkumar, A., Blossey, B., Ewer, J., ... Lal, A. (2007). Microprobe microsystem platform inserted during early metamorphosis to actuate insect flight muscle. *2007 IEEE 20th International Conference on Micro Electro Mechanical Systems (MEMS)*. doi: 10.1109/memsys.2007.4432976

Cao, F., & Sato, H. (2017). Remote radio controlled insect-computer hybrid legged robot. *2017 19th International Conference on Solid-State Sensors, Actuators and Microsystems (TRANSDUCERS)*. doi: 10.1109/transducers.2017.7993987

Dutta, A., De Keyser, R., & Nopens, I. (2012). Robust nonlinear extended prediction self-adaptive control (nepsac) of continuous bioreactors. In *Control & automation (med), 2012 20th mediterranean conference on* (pp. 658–664).

Erickson, J. C., Herrera, M., Bustamante, M., Shingiro, A., & Bowen, T. (2015). Effective stimulus parameters for directed locomotion in madagascar hissing cockroach biobot. *Plos One*, *10*(8). doi: 10.1371/journal.pone.0134348

Ionescu, C. M., Dutta, A., & De Keyser, R. (2012). Quantifying additive uncertainty in an identified multivariable model for closed loop control of depth of anesthesia. *IFAC Proceedings Volumes*, *45*(16), 577–582.

Kuwana, Y., Shimoyama, I., & Miura, H. (n.d.). Steering control of a mobile robot using insect antennae. *Proceedings 1995 IEEE/RSJ International Conference on Intelligent Robots and Systems. Human Robot Interaction and Cooperative Robots*, 530?535. doi: 10.1109/iros.1995.526267

Latif, T., & Bozkurt, A. (2012). Line following terrestrial insect biobots. *2012 Annual International Conference of the IEEE Engineering in Medicine and Biology Society*. doi: 10.1109/embc.2012.6346095

Sato, H. (2009). Remote radio control of insect flight. *Frontiers in Integrative Neuroscience*, *3*. doi: 10.3389/neuro.07.024.2009

Sato, H., Berry, C. W., Casey, B. E., Lavella, G., Yao, Y., Vandenbrooks, J. M., & Maharbiz, M. M. (2008). A cyborg beetle: Insect flight control through an implantable, tetherless microsystem. *2008 IEEE 21st International Conference on Micro Electro Mechanical Systems*. doi: 10.1109/memsys.2008.4443618

Sato, H., Kolev, S., Goehausen, N., Nyi, M. N., Massey, T. L., Abbeel, P., & Maharbiz, M. M. (2010). Cyborg beetles: The remote radio control of insect flight. *2010 IEEE Sensors*. doi: 10.1109/icsens.2010.5690991

Sato, H., & Maharbiz, M. M. (2010). Recent developments in the remote radio control of insect flight. *Frontiers in Neuroscience*, *4*. doi: 10.3389/fnins.2010.00199

Sato, H., Peeri, Y., Baghoomian, E., Berry, C., & Maharbiz, M. (2009). Radio-controlled cyborg beetles: A radio-frequency system for insect neural flight control. *2009 IEEE 22nd International Conference on Micro Electro Mechanical Systems*. doi: 10.1109/memsys.2009.4805357