R.R. Harrison, H. Fotowat, R. Chan, R.J. Kier, A. Leonardo, and F. Gabbiani, "A wireless neural/EMG telemetry system for freely moving insects," to appear in: *Proceedings of the 2010 IEEE International Symposium on Circuits and Systems (ISCAS 2010)*, Paris, France, 2010.

A Wireless Neural/EMG Telemetry System for Freely Moving Insects

Reid R. Harrison
Ryan J. Kier
University of Utah
Salt Lake City, UT 84112
harrison@ece.utah.edu

Anthony Leonardo
Janelia Farm Research Campus
Howard Hughes Medical Institute
Ashburn, VA 20147

Haleh Fotowat
Raymond Chan
Fabrizio Gabbiani
Baylor College of Medicine
Houston, TX 77030

***Abstract*—We have developed a miniature telemetry system that captures neural, EMG, and acceleration signals from a freely moving insect and transmits the data wirelessly to a remote digital receiver. The system is based on a custom low-power integrated circuit that amplifies and digitizes four biopotential signals as well as three acceleration signals from an off-chip MEMS accelerometer, and transmits this information over a wireless 920-MHz telemetry link. The unit weighs 0.79 g and runs for two hours on two small batteries. We have used this system to monitor neural and EMG signals in jumping and flying locusts.**

I. Introduction

Modern neuroscience research often relies on experiments using small animals such as mice and insects. For example, flying insects possess highly capable visual systems that perform complex, real time calculations to modulate flight control (see [1] and references therein). The study of insect visual processing during the past half century has provided rich insight into biological information processing strategies.

Measuring the weak extracellular electrical activity produced by neurons (typically in the range of 100 µV - 1 mV) or electromyograms (EMGs) in muscles (typically in the range of 1-10 mV) by traditional means has required large rack-mounted amplifiers and data acquisition systems. Due to the long wires connecting electrodes to remote amplifiers, most electrophysiology experiments must be performed inside a Faraday cage to achieve acceptable signal quality. Animals must be head-fixed or tethered during these experiments, which restricts the simultaneous study of neural activity and behavior.

As electronics have been miniaturized, efforts have been made to create small, lightweight amplifiers and wireless transmitters to permit electrophysiological monitoring during free behavior. Early designs used discrete components to provide analog telemetry of EMG signals from large flying moths [2], [3]. Simple RF beacons have been used to track dragonfly migration [4]. More recently, integrated circuits have been used to increase functionality (e.g., stimulating neurons in flying moths [5], [6]). To facilitate more sophisticated investigations into the neural control of behavior, we have developed an integrated circuit capable of amplifying two neural signals and two EMG signals from extracellular electrodes, digitizing these signals, adding parity bits for error detection, and wirelessly transmitting the digital information while operating from small, low-mass batteries.

II. Telemetry System Design

A. Integrated Circuit Design

We designed a custom integrated circuit for the telemetry system in a commercially available 0.6-µm BiCMOS process. Using low-mass batteries imposes severe power limits on the design of the chip: small batteries have low capacities and high internal resistance; pulling too much current can cause a battery's voltage to collapse immediately, regardless of its capacity. After testing many battery types, we opted to use 1.5V silver oxide batteries (Energizer 337) having a mass of 130 mg each and a volume of 29 mm^3. While these batteries have a stated capacity of 8.3 mAh, drawing 1 mA from the battery reduces its capacity to 3 mAh. Currents greater than 2 mA cause large drops in battery voltage and cannot be used. We use two batteries to provide a 3.0V supply.

Four fully-integrated low-noise amplifiers (see Fig. 1) are used to boost and filter the neural and EMG signals obtained from differential electrodes. Three operational transconductance amplifiers (OTAs) used in the circuit are current-mirror OTAs designed for low-noise operation by proper sizing of differential pair and current mirror transistors [7]. The gain of the first stage is set by the C_1/C_2 ratio; the second-stage gain is set by C_3/C_4. Bias generators set the high-frequency cutoff (through G_{m1} and G_{m2}) and low-frequency cutoff (through G_{m3}) of each amplifier. The G_{m3} OTA was placed in the second stage so its noise contribution is attenuated by C_1/C_2 when referred to the input [8]. The gain of the EMG amplifiers was set to 100; the gain of the neural amplifiers was set to 1000. Measured CMRR at 1 kHz (averaged across 10 amplifiers) was 74 dB; PSRR was 63 dB.

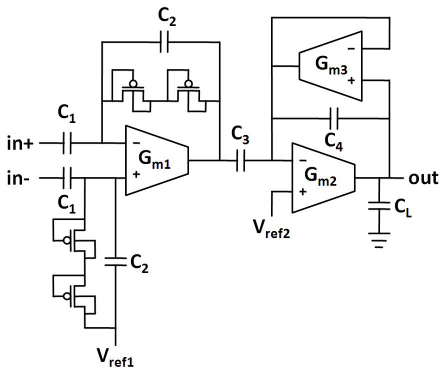

Figure 1. Schematic of low-noise biopotential amplifier. Operational transconductance amplifiers (OTAs) are designed according to [6].

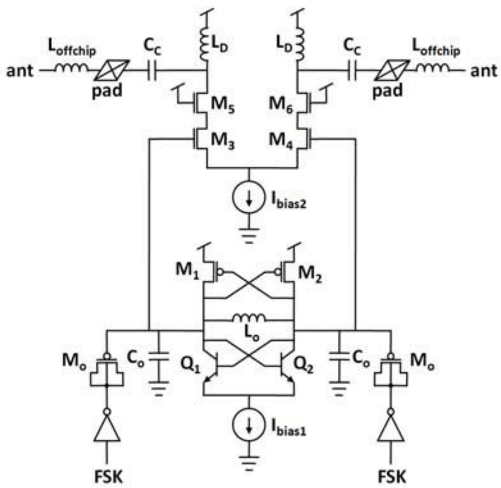

Figure 2. Schematic of 920-MHz FSK transmitter. Varactors (M_o) shift the resonant frequency of an open-loop negative-resistance *LC* oscillator.

A 9-bit successive-approximation register (SAR) ADC with capacitive DAC is used to digitize the amplified waveforms. A state machine controls an analog multiplexer and samples the neural signals at a faster rate (11.52 kS/s) than the slower EMG signals (1.92 kS/s). The ADC also samples (at 1.92 kS/s) three auxiliary input pins that are used to interface a commercially-available 3-axis MEMS accelerometer (Analog Devices ADXL330) with the chip to provide information on insect movement. The sampling rates are set by a low-power crystal oscillator using an off-chip 11.0592 MHz quartz crystal and drawing only 65 µA from the supply. For every 9-bit sample a parity bit is added to permit error detection. Frame marker bits are added, and the resulting 345.6 kb/s serial bit stream is passed to an on-chip frequency-shift keying (FSK) transmitter (see Fig. 2). Table I summarizes the dynamic range, bandwidth, sampling rate, and input-referred noise of each channel.

The core of the 920-MHz transmitter is an *LC* oscillator that uses a thick top metal layer to build a low-loss 26 nH inductor L_o ($Q \approx 11$). The use of a tank with a high *LQ* product, along with vertical *npn* transistors (Q_1 and Q_2) providing a high g_m/I ratio with relatively low parasitic capacitance allows this circuit to oscillate reliably with a bias current of only 180 µA. Small MOS varactors (M_o) are used to create a 600 kHz frequency deviation in response to a binary input. To save power, a PLL was not implemented and the oscillator operates in open loop. The measured frequency drift with supply voltage was -2.8 ppm/mV. The batteries have a very flat discharge curve, so frequency drift over time is measureable but not severe. A differential RF output stage with on-chip drain inductors (L_d = 26 nH) and series capacitors (C_C = 10 pF) is connected to an off-chip dipole antenna. Off-chip 56-nH inductors are used to improve radiation from the electrically short dipole. A die photograph of the 2.57 x 2.48mm^2 chip is shown in Fig. 3.

B. System-Level Design

Chips were packaged in a molded plastic 28-lead 5x5 mm^2 QFN package and mounted on a 13x9 mm^2 printed circuit board (PCB) along with battery holders, accelerometer, crystal, and antenna (see Fig. 4). The complete system with batteries weighs 0.79 g. The chip consumes 880 µA of current and the accelerometer consumes 320 µA, for a total of 1.2 mA. This limits battery life to 2 h of continuous use. The telemetry system can be temporarily mounted to an insect using wax, and electrode wires are soldered to the PCB.

TABLE I. TELEMETRY CHANNEL SPECIFICATIONS

Data Channel	Band-width	ADC Sampling Rate	Max. Range	ADC V_{LSB}	Input-Referred Noise
Neural Amps 1,2	300Hz-5.2kHz	11.52 kS/s	±1.2mV	4.69µV	2.3 µV_{rms}
EMG Amps 1,2	20Hz-280Hz	1.92 kS/s	±12mV	46.9µV	25 µV_{rms}
Acceler. X,Y,Z	DC-500 Hz	1.92 kS/s	±3.0g[1]	15.6mg	7.8 mg_{rms} (X,Y) 9.8 mg_{rms} (Z)

[1] 1 g = 9.81 m/s^2

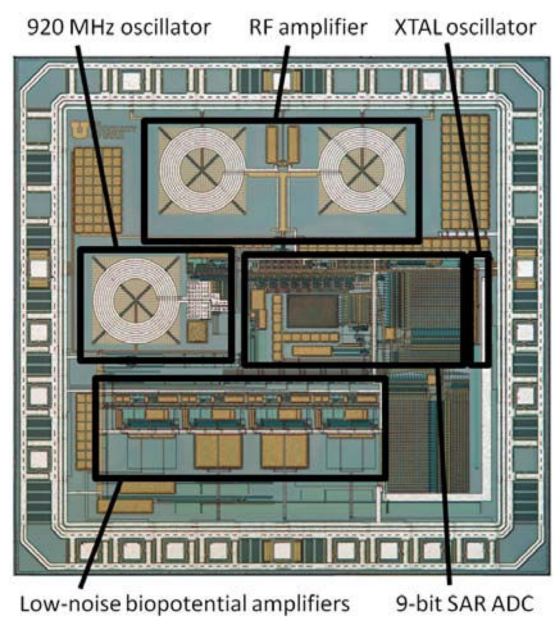

Figure 3. Die photo of 2.57 x 2.48mm^2 insect telemetry chip, fabricated in a 0.6-µm BiCMOS process.

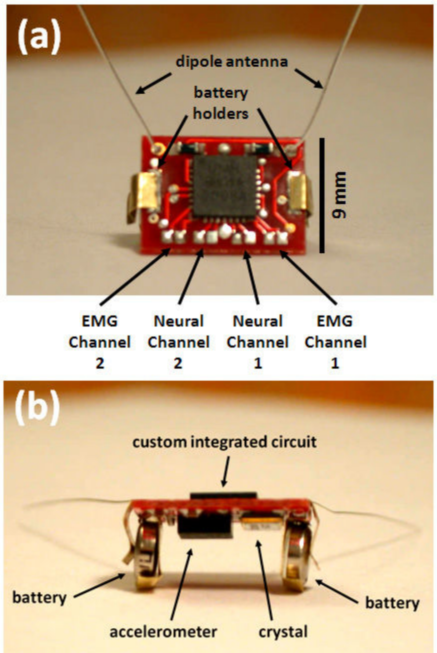

Figure 4. (a) Complete 13 x 9 mm^2 telemetry system with QFN-packaged chip. (b) Side view of telemetry system showing accelerometer and crystal.

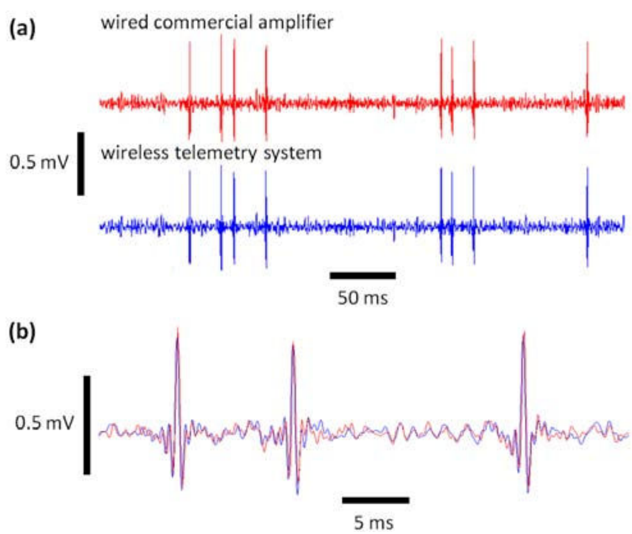

Figure 5. (a) Extracellular recording of spiking activity from neuron MDT1 in the dragonfly nerve cord, using wired commercial amplifier (red) and wireless telemetry system (blue). (b) Close-up comparison of three spikes.

III. Experimental Results

A. Recording from Dragonfly Nerve Cord

We performed initial tests of the telemetry system by recording neural activity from the target selective descending neuron MDT1 in the ventral nerve cord of a restrained dragonfly. A single 1.2 MΩ tungsten electrode was simultaneously monitored using a conventional wired amplifier (AM Systems 3600, 40 kHz sampling) and a neural amplifier channel from the wireless telemetry unit (see Fig. 5). The data matched very closely. A background noise level of 11.5 μV_{rms} was observed using the wired amplifier, while 12.1 μV_{rms} was observed using the wireless telemetry unit (over a bandwidth of 300 Hz to 5 kHz).

B. Recording from Freely-Jumping Locust

We used the wireless system to observe the activity evoked in an identified descending neuron (the DCMD) and two leg muscles in a locust presented with approaching objects simulated on a computer monitor [9]. The DCMD neuron is known to respond maximally to such stimuli, but its role in triggering escape behaviors remains unresolved, and its activity had never been recorded in freely escaping animals. Locusts were able to jump freely wearing the telemetry system (see Fig. 6), and data was not lost during the rapid movement. Fig. 7 shows example recordings obtained from a freely jumping locust using this system. In this example, the locust jumps approximately 50 ms before the simulated time of collision. During the approach, the neuron's activity gradually increases and is followed by the co-activation of flexor and extensor muscles, and then jump acceleration. By varying the stimulus parameters and measuring the neural and muscle activities, we found that the muscle co-contraction is triggered once the DCMD activity and stimulus angular size reach a threshold level, and take-off occurs after the extensor muscle generates enough spikes.

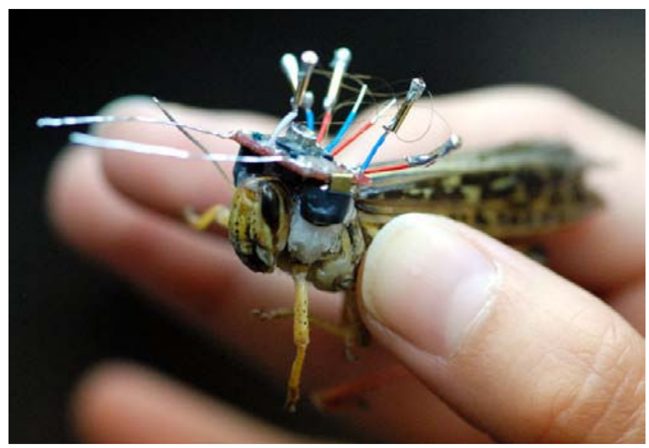

Figure 6. Telemetry system mounted on a locust *Schistocerca americana*.

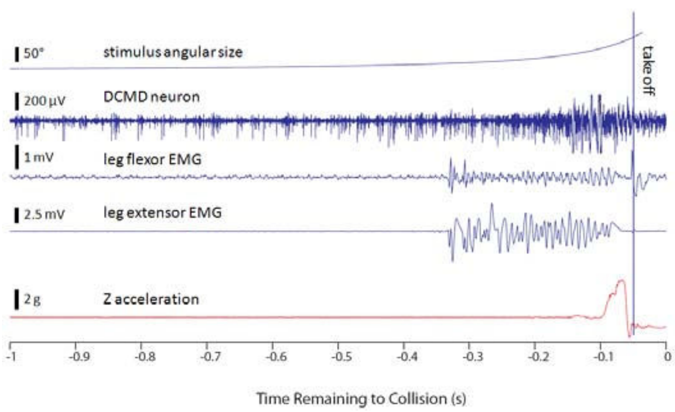

Figure 7. Data obtained wirelessly from a freely jumping locust, in response to an expanding visual stimulus (top trace). A neural signal from the DCMD neuron, plus two EMG signals were monitored (middle traces). Accelerometer data shows the jumping event (bottom trace).

Figure 8. Photograph of live wireless data acquisition from locust flying in wind tunnel. Wing beats are visible in EMG traces (center, left of finger). High-speed video of locust is synchronized to telemetry data.

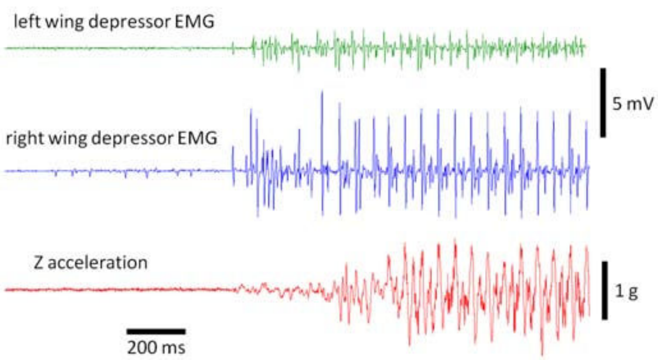

Figure 9. Data obtained wirelessly from a loosely tethered locust flying in a wind tunnel. Onset of 18 Hz wing beats is observed in the two wing EMG traces (top) and acceleration trace (bottom).

C. *Recording from Loosely-Tethered Flying Locust*

We have also used the system to observe wing muscle EMGs (and corresponding body acceleration) during loosely tethered flight in a low-speed wind tunnel (see Fig. 8). Muscle activity in the right and left wing depressor muscles occurs in synchrony with the wing beats (and corresponding body acceleration) at approximately 18 Hz during flight (see Fig. 9).

IV. CONCLUSIONS

Table II summarizes the measured performance of the miniature telemetry system. Fig. 10 shows the custom RF receiver with USB interface built to collect the wireless data. An audio port allows for real-time monitoring of neural or EMG signals over headphones during experiments. The small size and low mass of this device will enable new experiments in the study of the neural control of behavior. Future design efforts will focus on lowering the supply voltage of the integrated circuit to allow single-battery (i.e., 1.5V) operation to further reduce size and mass. However, since no commercial accelerometers operate below 1.8V, a next-generation device may lose the ability to report body acceleration.

TABLE II. TELEMETRY TRANSMITTER MEASURED PERFORMANCE

Supply voltage	3.0 V
Supply current (chip only, without accelerometer)	0.88 mA
Supply current (complete system, with accelerometer)	1.2 mA
Transmit frequency	920 MHz
FSK modulation depth	600 kHz
Telemetry data rate	345.6 kb/s
Telemetry range (using low-gain, omnidirectional receive antenna)	~2 m
Total system mass (including PCB, accelerometer, crystal, batteries)	0.79 g
Battery life	2 h

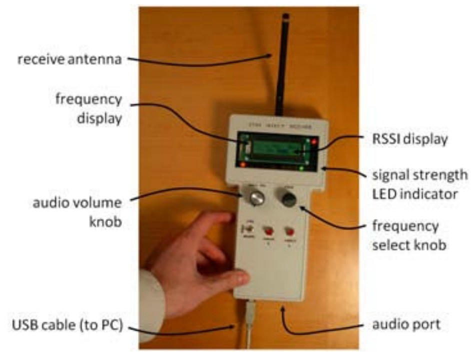

Figure 10. Custom wireless telemetry receiver with USB interface to PC.

ACKNOWLEDGMENT

This work was funded by AFRL contract #FA8651-07-1-0007, National Science Foundation contract NSF-IOB-0516775, the Human Frontier Science Program contract HFSP-RGP0016, and the Howard Hughes Medical Institute.

REFERENCES

[1] R. Olberg, R.C. Seaman, M.I. Coats, and A.F. Henry, "Eye movements and target fixation during dragonfly prey interception flights," *J. Comp. Phys. A,* vol. 193, no. 7, pp. 685-693, 2007.

[2] W. Kutsch, G. Schwarz, H. Fischer, and H. Kautz, "Wireless transmission of muscle potentials during free flight of a locust," *J. Exp. Biol.,* vol. 185, pp. 367-373, 1993.

[3] Y. Kuwana, N. Ando, R. Kanzaki, and I. Shimoyama, "A radiotelemetry system for muscle potential recordings from freely flying insects," In: *Proc. BMES/EMBS Conf.,* vol. 2, p. 846, Oct. 1999.

[4] M. Wikelski, D. Moskowitz, J.S. Adelman, J. Cochran, D.S. Wilcove, and M.L. May, "Simple rules guide dragonfly migration," *Biology Letters,* vol. 2, pp. 325-329, 2006.

[5] J. Mavoori, B. Millard, J. Longnion, T. Daniel, and C. Diorio, "A miniature implantable computer for functional electrical stimulation and recording of neuromuscular activity," In: *Proc. IEEE Intl. Workshop Biomedical Circuits and Systems,* pp. 13-16, Dec. 2004.

[6] D.C. Daly, P.P. Mercier, M. Bhardwaj, A.L. Stone, J. Voldman, R.B. Levine, J.G. Hidebrand, and A.P. Chandrakasan, "A pulsed UWB receiver SoC for insect motion control," *ISSCC Dig. Tech. Papers,* pp. 200-201, Feb. 2009.

[7] R.R. Harrison and C. Charles, "A low-power, low-noise CMOS amplifier for neural recording applications," *IEEE J. Solid-State Circuits,* vol. 38, no. 6, pp. 958-965, June 2003.

[8] R.R. Harrison, "The design of integrated circuits to observe brain activity," *Proc. of the IEEE,* vol. 96, pp. 1203-1216, July 2008.

[9] H. Fotowat, R.R. Harrison, and F. Gabbiani, "Measuring neural correlates of insect escape behaviors using a miniature telemetry system," In: *Proc. 35th Annual Northeast Bioengineering Conf.,* Cambridge, MA, Apr. 2009.