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A Wirelessly-Powered Homecage with Animal behavior Analysis and Closed-Loop Power Control

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Abstract

This paper presents a new EnerCage-homecage system, EnerCage-HC2, for longitudinal electrophysiology data acquisition experiments on small freely moving animal subjects, such as rodents. EnerCage-HC2 is equipped with multi-coil wireless power transmission (WPT), closed-loop power control, bidirectional data communication via Bluetooth Low Energy (BLE), and Microsoft Kinect® based animal behavior tracking and analysis. The EnerCage-HC2 achieves a homogeneous power transfer efficiency (PTE) of 14% on average, with ~42 mW power delivered

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to the load (PDL) at a nominal height of 7 cm by the closed-loop power control mechanism. The Microsoft Kinect® behavioral analysis algorithm can not only track the animal position in real-time but also classify 5 different types of rodent behaviors: standstill, walking, grooming, rearing, and rotating. A proof-of-concept in vivo experiment was conducted on two awake freely behaving rats while successfully operating a one-channel stimulator and generating an ethogram.

I. Introduction

A significant number of today's basic science and preclinical research experiments are conducted on awake and behaving small animal subjects, such as rodents, to observe the effects of various interventions on the behavior or physiology of the biological system in their natural state [1]. To monitor vital signs, behaviors, phenotypes, and physiological parameters, sensors and actuators that are either installed in the experimental arena or attached to or implanted in the animal's body, are required. For implanted devices, most *in vivo* experiments follow a similar routine: 1) transfer the animal subject from its homecage in the animal facility to the experimental arena; 2) attach cables, connectors, reservoirs, or wireless modules; 3) closely observe the animal behavior during the training or data collection period; 4) detach everything from the animal; and 5) return it back to the homecage in the animal facility [2]. This routine, which needs to be repeated for multiple sessions and multiple subjects, creates a stressful environment for the animal subjects that may bias their natural behavior and the outcomes of the research [3]. Long-term experiments can become especially labor intensive and time consuming for researchers [4]. If any portion of the aforementioned procedure can be shortened or automated, the quality of the experimental results can be improved. Several comprehensive homecage systems in various dimensions have been developed [5]–[7]. These systems, which have modular architectures, can alleviate limitations over the size and shape of the experimental arena. However, the animal subject's position need to be tracked in real-time to switch the coils, which increases the system complexity, and may influence the system reliability.

A new EnerCage-homecage system, called EnerCage-HC2, which is built around a standard homecage is presented. It can continuously power up and communicate with any devices implanted in or carried on the animal's body, as shown in Fig. 1. A novel multi-coil design around the homecage automatically focuses the transmitted electromagnetic power from a single transmitter (Tx) coil at the bottom of the homecage toward a pair of receiver (Rx) coils, carried on the animal head, obviating the need to switch the coils. Moreover, a closed-loop power control (CLPC) mechanism is established between the Tx-Rx power management circuits to cover the entire volume inside the homecage with a stable amount of power delivered to the load (PDL) in 10s of mW range despite animal movements [8]. A Microsoft (MS) Kinect®-based image processing algorithm is integrated with EnerCage-HC2 as a new module. It is capable of tracking the animal position in real-time and analyzing its behavior based on 2D (RGB) and depth image data. The intention of this module is to help biomedical researchers conduct their observations more easily and with high precision [9].

II. EnerCage-HC2 System Overview

A. Hardware

Fig. 2 shows a simplified schematic diagram of EnerCage-HC2. The driver block includes a Class-C power amplifier (PA), operating at 13.56 MHz, a CC2541 microcontroller (MCU) (Texas Instruments, Dallas, TX), and a digitally-controlled DC-DC converter (LTC3115) that can adjust the PA supply voltage, V_{PA} , to adjust its output power in 256 steps. A rectangular-shaped wire-wound Tx coil (L_1), is driven by the Class-C PA. The other four Tx coils ($L_{21}\sim L_{24}$) are electrically floating, along with their resonance capacitors, forming high-Q Tx resonators. $L_{21}\sim L_{24}$ are divided into two equal-length segments linked with small capacitors in a way that the length of each segment is much less than the wavelength of the carrier signals. This is done to avoid electromagnetic field cancellation at the Rx location, caused by the varying current phase in a large conductive loop [10].

On the Rx side, the high-Q Rx resonator (L_3), together with the Rx coil (L_4) and $L_{21}\sim L_{24}$ establishes the 4-coil inductive link. This configuration increases the power transmission efficiency (PTE) in comparison to a similarly sized 2-coil inductive link. A small receiver, used for electrical stimulation is carried by the awake behaving rat in the form of a headstage. Two Rx coils wirelessly receive powered through the 4-coil inductive link in near-field regime at 13.56 MHz.

The headstage, equipped with a CC2541 MCU, establishes a bidirectional BLE communication link with a personal computer (PC) that is equipped with a CC2540 MCU dongle. A full-wave rectifier is used to provide a DC voltage, V_{rec} , from the 13.56 MHz carrier. An adjustable regulator (TPS 79901) offers a stable DC voltage, V_{dd} of 3.3 V, for powering the CC2541 MCU. For biphasic electrical stimulation, the NPN and PNP transistors are alternately turned on, delivering charge to the tissue and removing it through a 10 μ F capacitor for charge balancing. The built-in ADC of CC2541 MCU, which is activated during stimulation, takes one sample from V_{rec} and a burst of eight consecutive samples from the 1 k Ω current sense resistor (2 and 6 samples during the anodic and cathodic phases, respectively) with 60 μ s spacing. These samples are then packetized and sent to the PC-GUI via BLE every 10 ms for the CLPC and functionality verification.

B. Firmware

Fig. 3a shows a simplified flowchart of the CLPC algorithm, which includes two BLE links among three CC254X MCUs. Upon receiving the user command, the graphical user interface (GUI) first establishes the BLE1 connection between the PC dongle and headstage MCU, and then establishes the BLE2 connection between the PC dongle and driver MCU. Once BLE1 is in place, the CC2541 built-in ADC in the headstage samples the onboard attenuated V_{rec} as well as the voltage across the 1 k Ω sensing resistor at 100 Hz each, and sends them to the PC. The PC stores the acquired data from the headstage and demonstrates it on the GUI in real time. The algorithm running on the driver MCU compares V_{rec} that is delivered from PC via BLE2 with a user-defined window. The driver MCU, which controls the DC-DC converter, then increases or decreases the V_{PA} based on the incoming V_{rec} data

to ensure that it remains within the desired range despite animal movements or load variations.

A simplified flowchart of the Kinect module for real-time behavior analysis of small freely moving animals is shown in Fig. 3b. Depth image captured by Kinect is used in rodent positioning and feature extraction. The algorithm first acquires the rodent body shape through a series of image processing techniques, such as background subtraction, thresholding, and contour finding. Then, centroid of the rodent body shape is calculated to be used as the subject position in tracking. Moreover, five types of features are extracted from the body shape, including body area, body radius, circularity, speed of centroid, and ellipticity. With those features being the input, a support vector machine (SVM) model is constructed to classify the depth image into five types of behavior: standstill, walking, grooming, rearing, and rotating. Both tracking and behavior recognition results are depicted on the GUI and stored for later use. The functionality and accuracy of the Kinect module was validated in previous experiments [9].

III. Experimental Results

Fig. 4 shows the *in vivo* experimental setup, including the EnerCage-HC2 prototype, MS-Kinect® and its fixture, and the 1-channel stimulating headstage. A 20 (Height) $\times$ 20 (width) $\times$ 42 (length) cm³ standard homecage is encompassed by five Tx coils. L₁ is mounted at the bottom of the homecage, driven by the Class-C PA. L₂₁~L₂₄ are adhered to the body of the homecage along with their resonance capacitors from outside. Because of the strong coupling between Tx resonators only one of them needs to have a variable capacitor for fine tuning of the entire Tx side at 13.56 MHz. Hence, the other resonators have fixed capacitors of 130 pF. This facilitates the manual calibration and optimal operation of the EnerCage-HC2 system.

The headstage was coated with medical grade epoxy, resulting in the overall weight of 5.1 g. L₃ is wrapped around the headstage printed circuit board (PCB) and L₄ is attached to the bottom of the headstage PCB. A 2-pin collar assembly (305/CP) with the length of 1.1 cm from PlasticsOne (Roanoke, VA) was connected mounted on the headstage PCB, as shown in Fig. 4 upper-right inset. MS-Kinect was installed on a PVC fixture at the optimal height of 110 cm (defined by the manufacturer) from the bottom of the homecage to cover the entire experimental arena. The animal tracking and behavioral analysis algorithm ran on the PC, while receiving the depth and RGB image data from Kinect.

A. In vitro Experiments

The required average DC power at the output of the headstage rectifier for the 1-ch wireless stimulator is 42 mW, when the stimulator delivers ~150 μ A positive pulse and ~40 μ A negative pulse with the stimulation frequency and pulse width of 100 Hz and 500 μ s, respectively. Fig. 5 shows the measured PDL when the stimulating headstage (Rx) is swept across the XY-plane at a height of $d = 7$ cm under two operating conditions: 1) Open-loop, i.e. without the CLPC, when Tx power was set at a constant level /of 0.47 W. 2) Closed-loop, when Tx power is dynamically adjusted by the CLPC to keep V_{ref} (and PDL) within a user-defined window. The results show that the EnerCage-HC2 can provide sufficient PDL

with high PTE to the Rx at the nominal distance of ~7 cm without holes or deep valleys in the wirelessly powered areas within the home cage.

B. In vivo Experiments

Two 16 week old male Sprague Dawley rats, weighing 330–350 g were used in this 4-hour pilot study, which was conducted with prior approval from the Institutional Animal Care and Use Committee (IACUC) at Emory University to test the functionality of the EnerCage-HC2 prototype and its wireless stimulating headstage. With a goal of eliciting an obvious motor effect of stimulation, each rat was implanted with a stainless steel monopolar stimulating electrode (MS303/1-AIU, PlasticsOne) in the primary motor cortex, with the bottom 0.75 mm uninsulated and the ground wire wrapped around a skull screw. As shown in Fig. 4 middle-right inset, later on we mounted the headstage on the rat's head by the 2-pin collar assembly. Before the *in vivo* experiment, the electrode impedance, measured in rat #1 and rat #2, were 17 k Ω , and 50 k Ω , respectively.

During the *in vivo* experiment, we repeatedly turned the stimulator on and off every 5 min while monitoring the rat's behavior. Therefore, each 10 min period includes one cycle of stimulation off and on. Two cycles of stimulation off and on are conducted on both rat #1 and rat #2, respectively. The type of behaviors of both rats were recorded by depth and RGB imagers at a rate of 10 frames/s in 5 min blocks, while the position was tracked and updated every 0.5 s.

1) Behavior Recognition Results—Fig. 6 shows the ethogram of rat #2 during a sample 20 min behavior analysis that includes 2 cycles of stimulation off and on. The rat's behavior type was recognized by the algorithm described in [9] and classified into five categories at 10 Hz with the assumption that animal behavior does not change within 0.1 s. As for the five types of behavior, we have also used a broader division by considering standstill as “inactive” and the other four types as “active”. Using this new division, the percentage of active time within each 5 min block is calculated and depicted. Also, the sum of distance that the rat has travelled is calculated and shown in Fig. 6, which has been derived from the rat trajectory.

Fig. 6 clearly shows the difference in rat #2 behavior when stimulation was on and off. With the stimulation off, rat #2 was highly active (77.7% and 79.2%). On the other hand, with the stimulation on, the activity rate rapidly fell to 27.9% and 16.7%, and most of time the rat behavior was categorized as standstill. The results of this behavior analysis also agree with the RGB and depth video streams captured by Kinect, which verify that the MS-Kinect based image processing algorithm can be used to track the rat and classify its 5 major behaviors.

Fig. 7 shows the average percentage of five type of behaviors over eight 5 min stimulation-off and four 5 min stimulation-on blocks for rats #1 and #2. It is shown that ‘Standstill’ is the dominant behavior in both stimulation off and stimulation on periods, with averaged percentage of 53.1% and 85.3%, respectively. Moreover, the average percentages of ‘Grooming’ and ‘Rearing’ in stimulation off period have increased 12.2% and 20.4%, respectively, compared to those when stimulation was on. By comparing these two bar

charts, the percentages of ‘Walking’ and ‘Rotating’ in stimulation off period (0.9% and 1.0%) are essentially unchanged, compared those in stimulation on period (0.8% and 1.6%).

2) Tracking Results—Fig. 8 compares the rat #2 trajectories during Period 1 with stimulation off/on and Period 2 with stimulation off/on. The rat travelled a longer distance when stimulation was off (318.7 cm and 288.0 cm) compared to when stimulation was on (134.1 cm and 103.7 cm). While the rat was under stimulation, it tended to stay around one end of the homecage, showing a reduction in the range of various activities.

IV. Conclusion

We have presented a new EnerCage-HC2 system that can reliably and wirelessly energize and communicate with a variety of electronic devices attached to or implanted in awake freely behaving small animal subjects for longitudinal electrophysiology and preclinical research. Because of the novel high-Q multi-coil segmented resonators, a homogeneously powered space is created without switching the active coils in earlier versions. With the integrated Kinect-based behavior analysis module, the system is capable of recognizing and registering 5 different behaviors over extended periods. Additionally, the CLPC mechanism based on two BLE links establishes bidirectional communication, and further stabilizes the power delivered to the Rx side. An *in vivo* experiment was conducted on two freely behaving rats, where the type of behavior and animal location were detected in our custom designed Kinect-based image analysis.

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Fig. 1.

A conceptual representation of the proposed EnerCage-HC2 system with Microsoft Kinect®.

Fig. 2.
Schematic diagram of the multi-coil inductive power transmission link along with other key blocks on the Tx and Rx sides.

Fig. 3.

(a) Simplified flowchart of the CLPC mechanism, as implemented in the firmware among three CC254X MCU with built-in BLE. (b) Simplified flowchart of the image processing software based on a MS-Kinect®.

Fig. 4.

The experimental setup with freely behaving rats and a 1-ch wireless stimulating headstage to test the EnerCage-HC2 system operation, particularly the CLPC and image processing based on MS-Kinect®.

Fig. 5. Measured PDL when Rx is swept across the XY-plane at a height of $d = 7$ cm without and with CLPC, when Tx power was constant at 0.47 W or varied by the CLPC as needed, respectively.

Fig. 6.

Ethogram of rat #2 in the homecage over 20 min. Stimulation status (ON/OFF) and distance travelled in this period are also depicted.

Fig. 7.

Averaged percentage of five types of behavior over eight 5-min stimulation-off and four 5-min stimulation-on blocks for rats #1 and #2.

Fig. 8.

Rat trajectories recorded by automated tracking from rat #2 movements within a standard homecage: (a) Period 1 and (b) Period 2.