# A Smart Homecage System with 3D Tracking for Long-Term Behavioral Experiments

Byunghun Lee, Mehdi Kiani, and Maysam Ghovanloo

***Abstract*— A wirelessly-powered homecage system, called the EnerCage-HC, that is equipped with multi-coil wireless power transfer, closed-loop power control, optical behavioral tracking, and a graphic user interface (GUI) is presented for long-term electrophysiology experiments. The EnerCage-HC system can wirelessly power a mobile unit attached to a small animal subject and also track its behavior in real-time as it is housed inside a standard homecage. The EnerCage-HC system is equipped with one central and four overlapping slanted wire-wound coils (WWCs) with optimal geometries to form 3- and 4-coil power transmission links while operating at 13.56 MHz. Utilizing multi- coil links increases the power transfer efficiency (PTE) compared to conventional 2-coil links and also reduces the number of power amplifiers (PAs) to only one, which significantly reduces the system complexity, cost, and dissipated heat. A Microsoft Kinect installed 90 cm above the homecage localizes the animal position and orientation with 1.6 cm accuracy. An *in vivo* experiment was conducted on a freely behaving rat by continuously delivering 24 mW to the mobile unit for > 7 hours inside a standard homecage.**

## I. Introduction

BEHAVIORAL neuroscience research on small awake animals, such as rodents or mice, has benefited from recent advances in neural interfacing . These neural interfaces traditionally use hard wires to power and communicate with instruments attached to the animal body, which are commonly called a mobile unit, thereby restricting experiments involving freely behaving animal subjects, and requiring labor-intensive observations in the long-term experiments [1]. In an attempt to overcome the limitations imposed by cables, several battery-powered neural recording systems have been developed [2], [3]. Although these setups can eliminate the cables from the mobile unit, they are still not suitable for longitudinal studies due to the limited lifetime of the batteries, which also add to the animal payload.

In order to address these limitations, a few wirelessly-powered systems have been developed to either directly power the interface electronics or recharge the batteries during the experiment [4]. Smart wirelessly-powered systems have been reported that can improve power transfer efficiency

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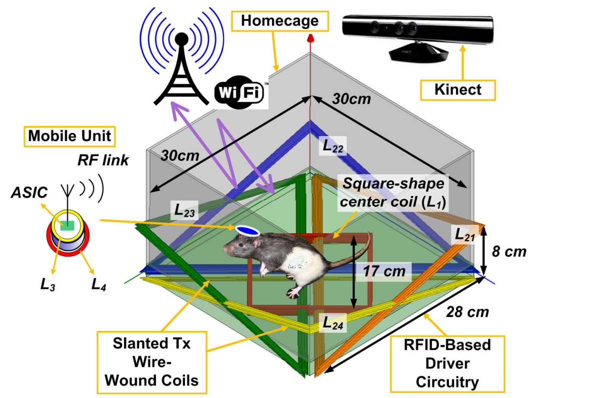

Fig. 1. 3D rendering view of the proposed EnerCage-HC system with animal tracking.

(PTE) [5], [6]. In these systems, batteries on the mobile units have been removed by utilizing an array of coils at the bottom of the experimental arena, which are automatically selected by the system based on the position of the animal subject. Although these systems have achieved efficient wireless power transfer, they are too bulky to be integrated with the standard homecage, and their animal tracking resolution is not sufficient for behavioral experiments.

Tracking animal subjects to analyze the locomotion has been studied on different species including rodents [7]. Automated locomotion measurement using computer vision-based systems has an obvious advantage over manual tracking in terms of lower labor costs, and it is rapidly growing. Microsoft Kinect® is a low-cost ($150) and popular commercial imager equipped with infrared (IR -3D) and Red-Green-Blue (RGB-2D) cameras, which allows experimentation in both bright and dark conditions. It has been recently adopted in automated locomotion tracking for the behavioral experiments [8], [9]. In this paper, we present a smart wirelessly-powered homecage, called the EnerCage-HC, shown in Fig. 1, which includes the Kinect for automated animal tracking and wirelessly powered mobile unit in a standard homecage with a geometrically- optimized wire-wound coil (WWC) array. The EnerCage-HC system is specifically designed for automated, high throughput, and long-term experiments in the standard homecage.

## II. EnerCage-HC System Architecture

Fig. 1 shows a rendered view of the proposed EnerCage-HC system. A square-shaped WWC ($L_1$) with the size of 17 cm is located in the center and four overlapping slanted WWCs ($L_{21}$~$L_{24}$) with 28 cm triangular shape are located around the four corners of the homecage to form 3-

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and 4-coil power transmission links with two coils ($L_3$, $L_4$) that are integrated on the mobile unit. In this system, $L_1$ is driven by a class-C power amplifier (PA) at $f_p$ = 13.56 MHz. When the position of the animal subject is detected on $L_1$, from Kinect images, $L_{21}$~$L_{24}$ WWCs are all open, and a 3-coil link is formed. However, when the animal is close to the homecage walls, one of $L_{21}$~$L_{24}$ WWCs is shorted with a capacitor to resonate at 13.56 MHz, and a 4-coil link is formed. The multi-coil link not only increases the PTE compared to similar-sized 2-coil links but also reduces the number of PAs to only one, which in turn reduces the system complexity, cost, and dissipated heat.

The stationary unit is composed of a coil array ($L_1$, $L_{21}$~ $L_{24}$) with resonance capacitors ($C_1$, $C_{21}$~ $C_{24}$), a controller unit, CLPC unit, a Microsoft Kinect for optical tracking, and a central PC station with a graphic-user interface (GUI). An IGLOO FPGA (Microsemi, Aliso Viejo, CA) receives the data corresponded to the animal position through WiFi from a PC. This data is the result of Kinect images processed using our localization program in MATLAB, and is used to activate or deactivate the four $L_{21}C_{21}$~ $L_{24}C_{24}$-tanks. The RFID reader not only drives the class-C PA, but also recovers the back telemetry (BT) data sent from the power management integrated circuit (PMIC) ASIC in the mobile unit. The PA supply voltage ($V_{DD}\_Tx$) is dynamically controlled by the closed-loop power control (CLPC) based on the BT data to compensate for any coupling distance and load variations [10]. The received BT data, which indicates that the received power in the mobile unit is more than sufficient, is over-sampled by the FPGA to decrease the $V_{DD}\_Tx$ at the rate of 320 Hz by controlling a digital potentiometer (AD5160) in the feedback loop of the DC-DC converter (LT1370). In the case of no BT data, FPGA increases the $V_{DD}\_Tx$. In this system, $V_{DD}\_Tx$ is adjustable from 4.5 V to 20 V in 256 steps. The WiFi module transfers the position data and $V_{DD}\_Tx$ digitized information between the FPGA and the PC to control the relay drivers for $L_{21}C_{21}$~$L_{24}C_{24}$-tanks. A wireless receiver operating at 2.4 GHz collects the mobile unit voltage information for monitoring purposes.

The mobile unit is equipped with the power management ASIC, two 0.21 F super-capacitors, a 3.3 V low-dropout regulator (LDO), an LED tracer, and an MCU (nRF24LE1). In the PMIC, the 13.56 MHz carrier is rectified by a positive/negative rectifier and stable $V_{DD}$ and $V_{SS}$ are generated from the on-chip LDOs. The positive rectifier voltage ($V_{RECP}$) is divided by two resistors (0.5 × $V_{RECP}$), and digitized by a built-in 10-bit ADC inside the MCU. When $V_{RECP}$ is higher than 2.3 V, the MCU sends short pulses to the PMIC at 3 kHz. A BT block in the PMIC generates sharp pulses (~0.4 µs) to short the $L_4C_4$-tank. This data is used for the CLPC. Measured $V_{RECP}$ is also sent wirelessly to the PC through a 2.4 GHz link for monitoring purposes.

Fig. 2 shows the measured PTE distribution inside the EnerCage-HC at 7 cm distance from the bottom of the homecage. The surface of homecage was marked by a checker board with 3 cm resolution for the PTE measurements. At the corners, the maximum measured PTE was 36.3%. The lowest and average PTEs were 16.1% and 21.9%, respectively. The efficiency of the PA was measured

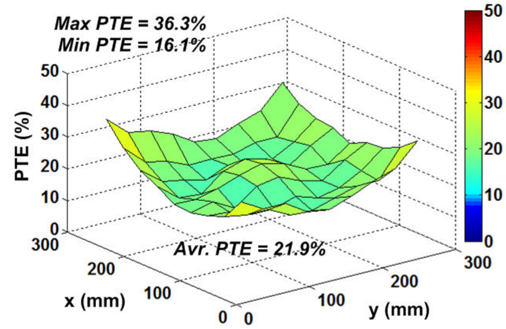

Fig. 2. Measured PTE distribution inside the EnerCage-HC at 7 cm distance from bottom of the homecage.

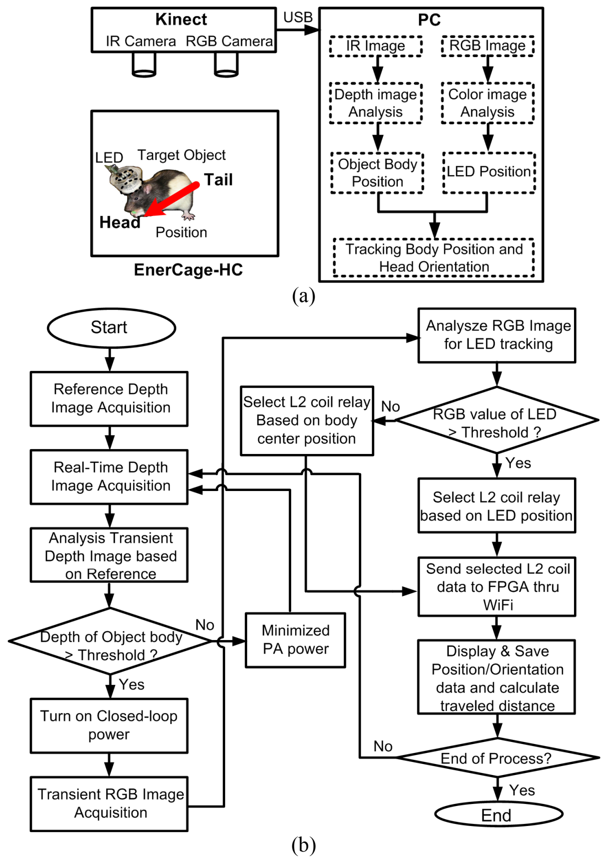

Fig. 3. (a) Hardware and (b) software diagrams of our tracking mechanism in the EnerCage-HC.

81% at $V_{DD}\_Tx$ = 4.5 V, and gradually decreased to 63% at $V_{DD}\_Tx$ = 20 V, which is the maximum voltage in this prototype EnerCage-HC system.

In the EnerCage-HC system, all acquired information such as mobile unit voltage, $V_{RECP}$, tracking results, $V_{DD}\_Tx$, and system operating status, such as WiFi connection and 2.4-GHz link are collected and transmitted to the PC through WiFi and the USB links from the Kinect and the wireless receiver to PC.

## III. Kinect-based 2D Animal Subject Tracking in EnerCage-HC System

Fig. 3 shows the hardware and software diagrams of the tracking algorithm in the EnerCage-HC system. The Kinect was installed at 90 cm height above the homecage and

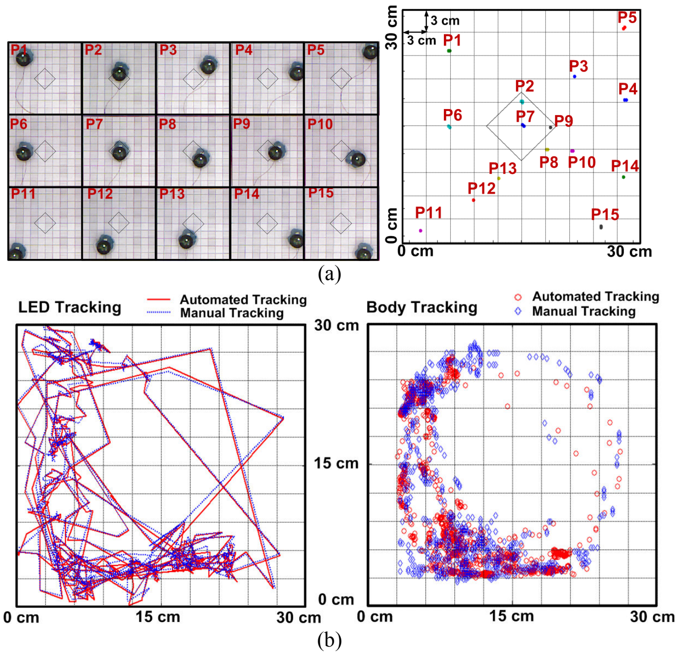


Fig. 4. Validation of the automated tracking in the EnerCage-HC system: (a) sample images of 15 positions (P1-P15) for the LED tracking on the checker board during 3 min, and (b) automated tracking vs. manual tracking for 20 min *in-vivo* experiment (LED and body tracking).

covered 30 cm × 30 cm area of the homecage. The collected depth and RGB images from the Kinect were transferred to PC to analyze the object's body and the LED indicator position as shown in Fig. 3a. In the software, the real-time depth image from the Kinect is compared to the reference depth image, which is taken when the animal subject is not present, to find the animal subject in the homecage. The software algorithm projects the depth image voxels over a 2D plane, and indicates the areas that have higher value than a predefined detection threshold.Then, the center of the animal outline is found from the projected image to identify the center of the subject body. If the measured depth of the object is less than the threshold, the software concludes that the animal is not present in the cage, and reduces the PA power to its minimum by setting $V_{DD}\_Tx$ = 4.5 V to reduce the dissipated power. When the software finds the center of the subject inside the homecage, it activates the CLPC to provide the sufficient amount of power to the mobile unit. It then analyzes the RGB image to find the LED indicator. At startup, when the mobile unit is not powered and the LED is off, $L_{21}$~$L_{24}$ are controlled based on the body position extracted from the depth image. When the LED indicator starts blinking, the position of the LED indicator is detected from the RGB image and combined with the center of the body to not only activate one of $L_{21}$~$L_{24}$ coils but also indicate the subject orientation. By tracing the acquired positions, the accumulated distance that the subject has traveled is calculated in real time. All of the acquired data during the experiment is displayed on the PC screen, and saved in PC for post processing.

Fig. 4 compares the automated and manual tracking results within the EnerCage-HC. A checker board with 3 cm grid was used to manually place the mobile unit in a known position inside the homecage. Fig. 4a shows the images of 15 random

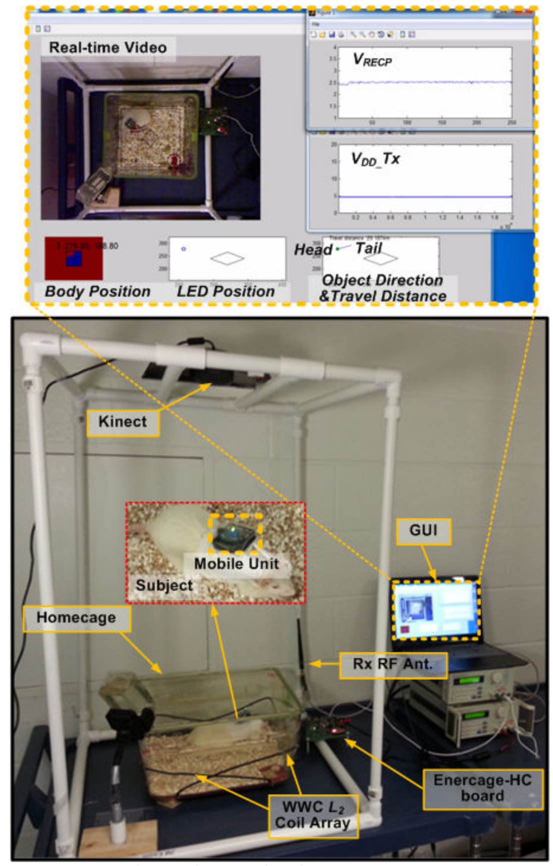


Fig. 5. *In vivo* experimental setup for the EnerCage-HC prototype. In this experiment, the rat was freely moving around the cage for 7 hr and 20 min.

mobile unit positions on the checker board compared with the automatic tracking data collected in 3 min at each position (P1 to P15). The maximum time jitter for the optical tracking was 20 ms in this test. The maximum position error was measured 1.6 cm near the corners, where the large viewing angle from the Kinect lens is the main source of inaccuracy. Fig. 4b shows the comparison between automatic (red) and manual frame-by-frame (blue) tracking of a freely behaving rat (17 cm long) from the recorded video in an *in vivo* experiment. We randomly selected 20 min of the 7 hours and 20 min of the experiment, and the manual tracking was separately performed on LED and center of body. It can be seen from Fig. 5b that the automated tracing of the LED indicator is in good agreement with manual tracking with maximum localization error of 1.3 cm. However, since determination of the manual body center is somewhat subjective, the automated and manual tracking results are not overlapping as well as the LED tracking. Nonetheless they show similar trends.

## IV. In Vivo Experiment for HomeCage-HC System

Fig. 5 shows the *in vivo* experimental setup for the EnerCage-HC prototype. The animal subject was a one-year-old Long-Evans rat weighting 300g. The mobile unit was placed in a plastic box and attached to a special jacket, designed for rats. All experiments were conducted with the prior approval from the Institutional Animal Care and Use Committee (IACUC) at the Georgia Institute of

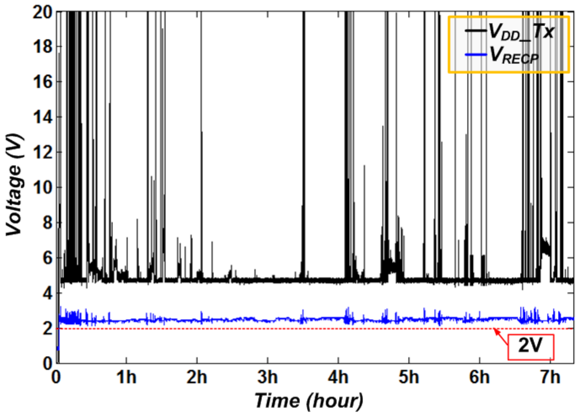


Fig. 6. *In vivo* experimental results showing the mobile unit positive rectifier voltage, $V_{RECP}$, and the transmitter PA supply voltage, $V_{DD}\_Tx$, during ~7 hrs.

Technology. During the experiment, the GUI reported the real-time video, $V_{RECP}$, $V_{DD}\_Tx$, and the LED/Body tracking information along with the rat body orientation and the travel distance. Water bottle and food dispenser were also placed in the homecage during our long-term experiment. During 7 hr and 20 min of the experiment, the rat was freely moving in the homecage.

Fig. 6 shows the measured $V_{RECP}$ and $V_{DD}\_Tx$ during 7 hrs and 20 min without any interruption. The EnerCage-HC continuously delivered 24 mW of regulated power to the mobile unit by maintaining $V_{RECP}$ constant at 2.3 V, which was high enough for the LDO to generate a stable $V_{DD}$ = 2 V, thanks to the CLPC module. The $V_{DD}\_Tx$ was dynamically adjusted by the CLPC module in the EnerCage-HC between 4.5 V and 20 V corresponding to PA power consumption of 0.3 W to 7 W.

Fig. 7 shows the measured tracking information including the position and orientation of the animal inside the homecage during 7:20 hr *in vivo* experiment. Fig. 7a shows the automated position data for the LED indicator on the mobile unit The heat map shows how long the animal spent in a certain location. The statistical result for the rat's orientation based on the automated LED/body tracking data is also shown in Fig. 7b. Since most of the time the rat moved across the left corners, marked A and B in Fig. 7a, the orientation of the rat shows peaks in those directions. The rat's travel distance based on the LED tracking data is shown in Fig. 7c, which indicates that the rat moved about 69.6 m in the homecage during the experiment.

## V. Conclusion

A novel wireless platform for electrophysiology experiments inside the standard homecage was presented. This system called the EnerCage-HC takes advantage of multi-coil coupling and Kinect-based optical localization to offer an efficient and low-cost technology for wireless powering any electronics attached to an animal subject as well as behavioral tracking of the subject. The functionality of the EnerCage-HC prototype was fully demonstrated in both bench-top and *in vivo* experiments. The proposed EnerCage-HC system has the ability to create an automated enriched environment inside standard homecage for long-term behavioral experiments.

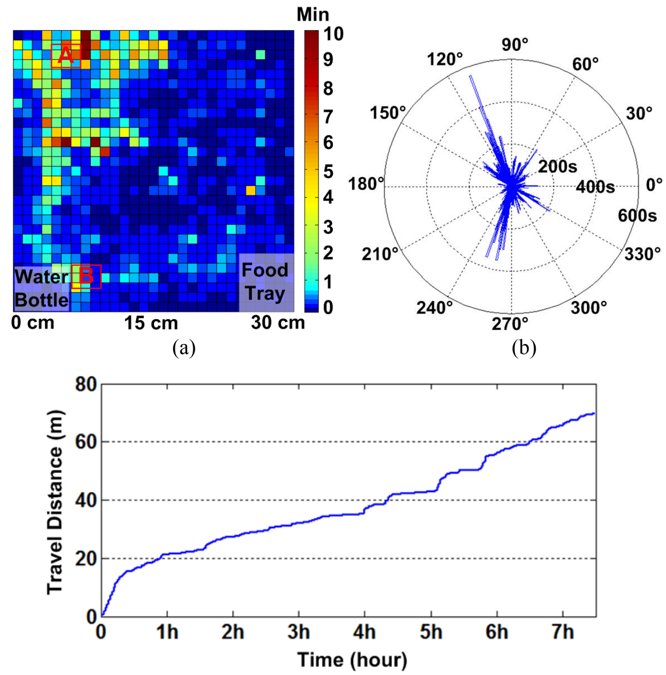


Fig. 7. *In vivo* experimental results showing the automated tracking for the LED/body during ~7 hrs of the experiment inside the homecage: (a) the position of the mobile unit based on the LED tracking, (b) the distributed time of the rat's orientation based on the LED/body tracking, and (c) the travel distance of the rat in the homecage.

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