Characterization of Passive Wireless Electrocardiogram Acquisition in Adult Zebrafish

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***Abstract*—Zebrafish have been demonstrated as an ideal vertebrate model system for a wide range of bio-studies. Along with conventional approaches, monitoring and analysis of zebrafish electrocardiogram (ECG) have been utilized for cardio-physiological screening and elucidation. However, existing approaches involving the use of anesthesia failed to provide intrinsic ECG signals. In this work, we propose and characterize wireless power transfer (WPT) via inductive coupling to power an ECG zebrafish implant and a backscattering mechanism for data communication. The inductive link was realized using the solenoid configuration to resolve misalignment issues. Power transfer efficiency (PTE) was characterized and test data were successfully obtained in different practical scenario. Therefore, we speculate our approach would pave the way for continuous ECG monitoring of freely-swimming zebrafish without disrupting their normal activities, supporting various biological investigations.**

***Index Terms*— Zebrafish; Electrocardiogram; Inductive Coupling; Wireless Power Transfer; Backscattering.**

I. Introduction

The zebrafish (*Dario rerio*) model has been playing an important role for biological studies, because of its small size, short generation time, and amenable genetics. Zebrafish hearts can fully regenerate after ventricular injuries, thus contributing a precious tractable model system to study endogenous heart regeneration [1]. Furthermore, zebrafish have also proven to be an ideal vertebrate model system for wide range of biological investigations in neuroscience, cardiology and developmental biology owing to their fecundity, morphological and physiological similarity to mammals and the complexity of the circadian clock in relation to behavioral, sleep cycle, cellular and molecular responses [2]. The zebrafish model enabled a forward genetic approach to reveal the genetic basis and underlying molecular mechanisms of a host of heart diseases, including arrhythmic diseases which contributed about 350,000 deaths annually in the U.S. only [3]. Further, it has been proven to be a low-cost and efficient animal model system compared to others [4]. Last but not least, cardiac toxicology is extremely important in drug discoveries and studying the environmental effects [4], and zebrafish has been thoroughly investigated, providing evidence-based capability [2].

Conventionally, the adult zebrafish myocardium was assessed and analyzed via heart slides and/or molecular biology approaches. Although possessing advantages, those methods fail in studying the progress of the process (i.e. regeneration and remodeling) of same subjects over time. Further, they cannot indicate functionalities of the entire heart. In the last several years, our laboratory and others have been demonstrating the use of electrocardiogram (ECG) to study zebrafish hearts in long term. Specifically, parylene-based microelectrode array (MEA) membranes were used, providing ECG signals with high spatial and temporal resolution, as well as favorable signal-to-noise ratio (SNR) [5]. The acquired data were distinguishable between heart-injured and control fish; thus enabling studies of heart regeneration and other cardiac diseases. However, the experimental setup required anesthetized animals, rendering the existing systems inadequate to provide intrinsic ECG signals which are critical for bio-studies.

Our group has been pioneering in the development of wired and wireless ECG systems for real-time ECG monitoring in small animal models, such as zebrafish and neonatal mice [5-8]. In our endeavor reported in [8], we have demonstrated a wireless ECG system for neonatal mice. Solenoids were used to minimize the misalignment issues which were critical to planar antennas [9]. Further, due to the limited area on small animals, a compact planar thin-film coil with a low quality factor (Q) would not be able to harvest enough energy via inductive coupling to operate the circuits. We employed optical transmission via an infrared light (880 nm) to transmit the signals and wireless ECG data were successfully obtained [8]. However, similar approaches would face challenges with the versatile and tiny zebrafish under water. Recently, we have successfully established a wireless power transfer (WPT) scheme to power a

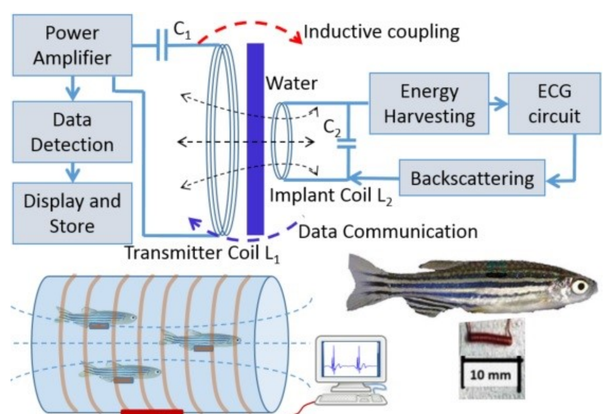

Fig. 1. Conceptual design of the entire system.

compact solenoid that can be worn by zebrafish [7]; however data communication has not been demonstrated. In this paper, we report our most recent efforts on developing the WPT and communication schemes for the wireless *zebrafish ECG jacket*. Our system consists of transmitter and receiver units, with resonating transmitter solenoid (TX) and receiver solenoid (RX), respectively. ECG data communication were realized via backscattering using the same inductive link. We characterized the entire system in various practical settings and used a simulated ECG signal to validate the communication link. The overall system with components and the conceptual design are illustrated in **Fig. 1**.

II. Design And Implementation

A. Transmitter and Receiver

The TX is 72 mm long with a diameter of Φ53 mm. It was made by winding AWG18 magnet wire around the cylindrical customized fish housing, providing a 58-turn 100-μH inductor (**Fig. 2, lower left**). The RX is a Φ3 mm × 20 mm solenoid made of 74 turns of AWG31 magnet wire, resulting in an inductance of 1.5 μH. Due to effects from water attenuation, the optimal frequency range for near-field inductive coupling WPT is between 1 and 30 MHz [9]. Here, we chose our operating frequency to be 1 MHz. Capacitors **C1** and **C2** were adjusted to tune the TX and RX coils resonate at 1 MHz. In order to drive the TX, we implemented the class-E amplifier topology shown in **Fig. 2** owing to its efficiency. **M1** is the IRF530 MOSFET (*Vishay Siliconix, Santa Clara, CA*). **L3** and **L4** have values of 24 μH and 44.65 μH, while **C3** and **C4** are capacitors with values of 625 pF and 773 pF, respectively. **R1** is a 46.73 Ω resistor. We used a function generator to drive **M1** with 1-MHz 5-Vpp 4-V-offset square waves. In order to produce DC power in the receiver end we implemented a full-wave rectifier design as seen in **Fig. 2. C5** and **C6** are both 10 nF. The diodes are 1N4148 switching diodes. The ECG output would be feedback to the RX for backscattering communication.

B. WPT and Backscattering Communication

The rectifier design allows the ECG output in terms of voltage to modulate onto both the positive and negative amplitude of the signal at **L2** and **C2.** When the voltage across **L2** and **C2** is positive, diode **D1** behaves like a short and diode **D2** allows any positive voltage of ECG output to be injected at a voltage value above half of the voltage across **L2** and **C2,** thus modulating the voltage across **L1** and **C1**. Due to the symmetry of the circuit, the same thing happens when the voltage across **L2** and **C2** is negative.

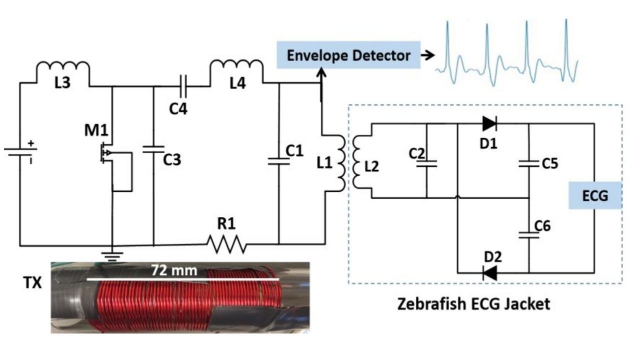

Fig. 2. Schematics of the transmitter (left), receiver (right), and the TX solenoid.

III. Experiments, Results and Discussion

A. PTE Characterization

We used a Vector Network Analyzer (*8753ES*, *Agilent Technologies, Santa Clara, CA*) to measure S_{21} at the resonance frequency (1 MHz) to characterize PTE. We measured at various misalignment angles between the TX and RX distributed symmetrically between −90 and 90 degrees. Based on our calculations, a one-channel ECG implant with a differential amplifier and a bandpass filter would need ~200 μW of power to operate. Assuming we are sending out 1 W of power, the S_{21} value (in dB) would need to be above

$$S_{21} > 10\log\left(\frac{200\ \mu W}{1\ W}\right) = -37\ dB$$

Therefore, ideally we would need to achieve $S_{21} > -37$ dB for every possible misalignment angle between the transmitter and receiver to ensure continuous powering and communication. In **Fig. 3b,** we can see that the efficiency never drops below −37 dB. As can also be seen from **Fig. 3**, at most of the misalignment angles, S_{21} was above −33 dB, corresponding to 500 μW of receiving power. This provides additional room for us to add more electronic components for other sensors or for multiple-channel recording. Further, we do not really need to maintain second-by-second ECG recording for investigations, thus practically, a smaller RX could be considered.

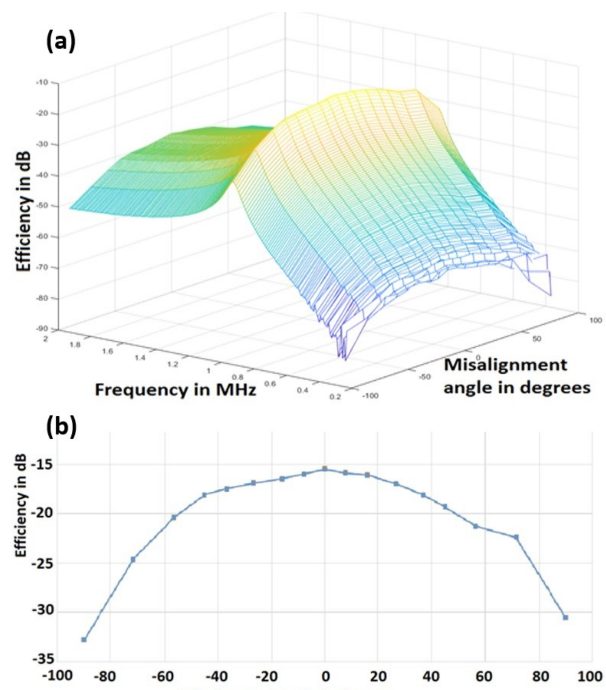

Fig. 3. a) 3D plot showing PTE at various misalignment angles and frequencies. b) PTE at 1 MHz at misalignment angles.

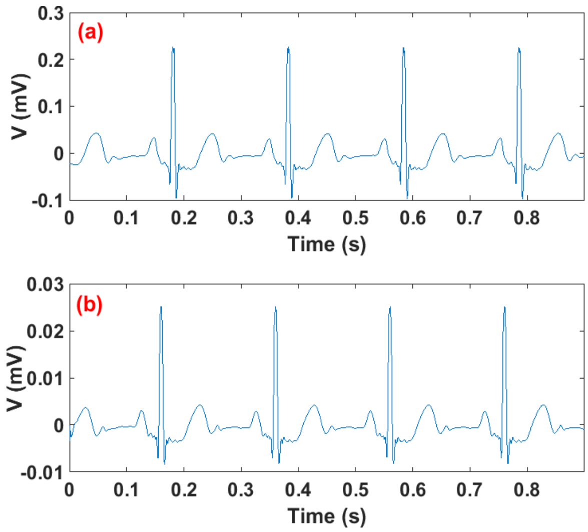

Fig. 4. Backscattered ECG signal after de-noising in air at misalignment angles of (a) 0 degrees and (b) 45 degrees.

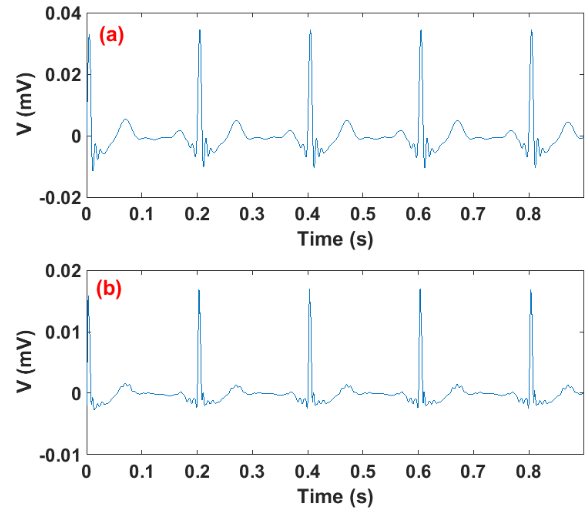

Fig. 5. Backscattered ECG signal after de-noising in water at misalignment angles of (a) 0 degrees and (b) 45 degrees.

B. Backscattering Communication

We characterized the backscattering communication in both air and water environments for ECG data transfer via the inductive link at various degrees of misalignment angles between the TX and RX. An ECG simulator was used to feed the signal to the RX to be sent back. The obtained signals were de-noised using the wavelet technique which has been extensively deployed in our laboratory for processing weak physiological signals [5]. The results are shown in **Figs. 4** and **5**, for air and aquatic environments, at 0 and 45 degrees, respectively.

It is obvious that in all cases shown in **Figs. 4** and **5**, the ECG signal was successfully received and de-noised, showing full features of P waves, QRS complexes and T waves. We can also see that water did not significantly affect the signal quality. We lost some features, such as P and T waves, at some critical angles in the aquatic environment; however, as aforementioned, continuous acquisition is not required and zebrafish keep changing their position/orientation all the time. In real scenarios, the motion artifacts caused by movement may add some interference; however those are in low-frequency ranges, which could be easily filtered out by the wavelet technique [5].

IV. Conclusions

The results have shown that our proposed approach is capable of delivering sufficient power to the *zebrafish ECG jacket* for both ECG recording and backscattering communication, despite the environment and misalignment. This holds promise to carry out numerous biological studies and drug testing using the zebrafish model. Our future work includes the miniaturization of the entire system on the parylene C substrate [5] so that actual ECG monitoring of freely-moving zebrafish can be achieved.

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