Direct 3D-Write Technology for MRI-Compatible Flexible Electronics: Advancing Dynamic Imaging and Wearable Electrocardiograms

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Abstract

Recent advances in mid-field magnetic resonance imaging (MRI) have reduced costs and improved portability, factors that have traditionally inhibited its clinical usage. With these developments, demand for MRI has steadily grown for applications like surgery and diagnostics. This work aims to improve MRI coils and develop an MRI-compatible, wearable electrocardiogram (ECG) by utilizing 3D-Write technology. For our MRI coil, we utilized silver inks to reduce cost and improve flexibility, further democratizing another aspect of MRI for clinical adoption. Our silver ink selection and coil geometry design allowed for these improvements—when tested via MRI, our coils demonstrated improved imaging compared to industry standards. MRI-compatible ECG's aim to overcome the noise derived from the magnetohydrodynamic effect. This development provides essential equipment for the budding field of MRI-guided surgery. We also have chosen to design our ECG as a wearable device for its small form-factor and wireless data transmission. Current tests have demonstrated accurate data collection and wearability. Both technologies were designed using 3D-write technology, and this allows for the fabrication of complex geometries for electrode and coil designs. Specifically, the low tolerance specifications and the variety of materials allowed for rapid testing, scalability ease, and precision fabrication.

I. Fabrication with Direct 3D-Write Technology

We used a Voltera NOVA to direct 3D-write with conductive, semi-sintering silver ink onto thermoplastic urethane substrates (TPU), as shown in **Figure 1**. For the receiver coil and electrocardiogram (ECG), we used a conductive ink (σ = 16.6 MS/m, ACI Materials) and a flexible ink (σ = 7.9 MS/m, Voltera), respectively. After curing the thin (~200μm) ink layer, we interfaced our MRI coil to a radiofrequency detuning board via conductive copper tape. For our ECG, we interfaced the electrodes to our microcontroller using a ribbon cable—in addition, we used another TPU substrate to mask traces while offering access to the electrodes

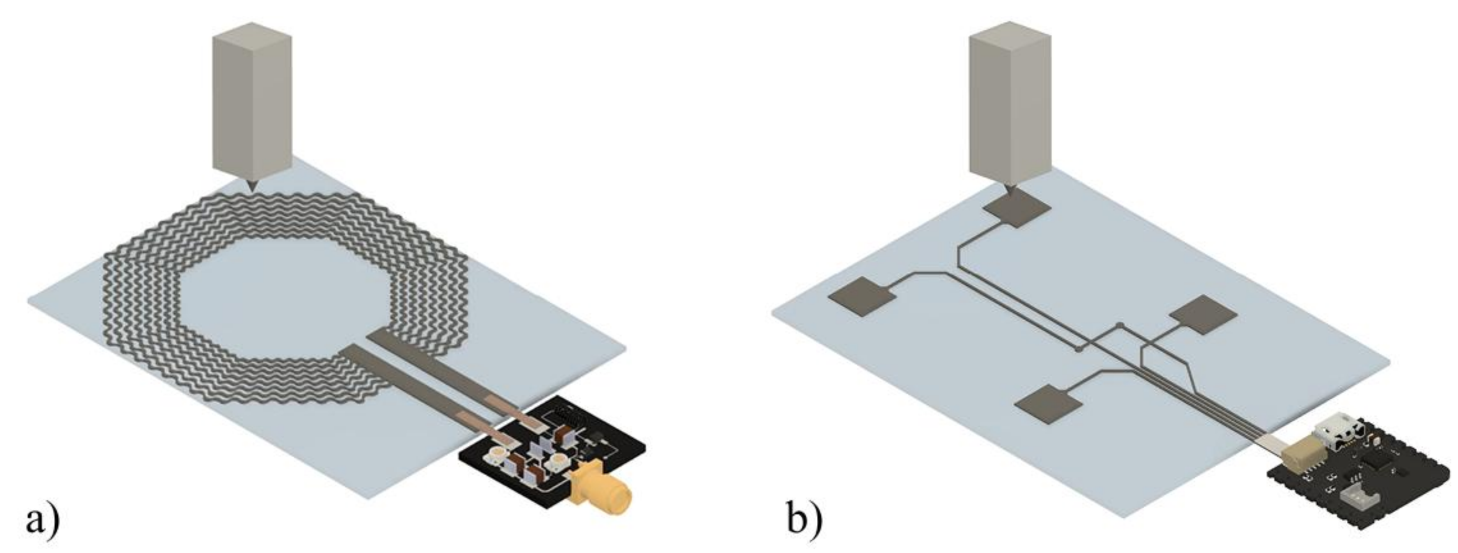

Fig. 1. Fabrication procedure for a) MRI Receiver Coil and b) MRI-Compatible Electrocardiogram

II. Flexible, Receiver Coil for MRI Imaging

As our coils are combined in an array, we must phase shift each coil to preserve signal integrity and prevent interference. To accomplish this, we utilized a π-phase shifter to shift each coil by 130° in our base circuit and added a variable capacitor to additionally shift each coil ±20° to account for individual coil variance. We integrated this design into a printed circuit board as shown in **Figure 2**.

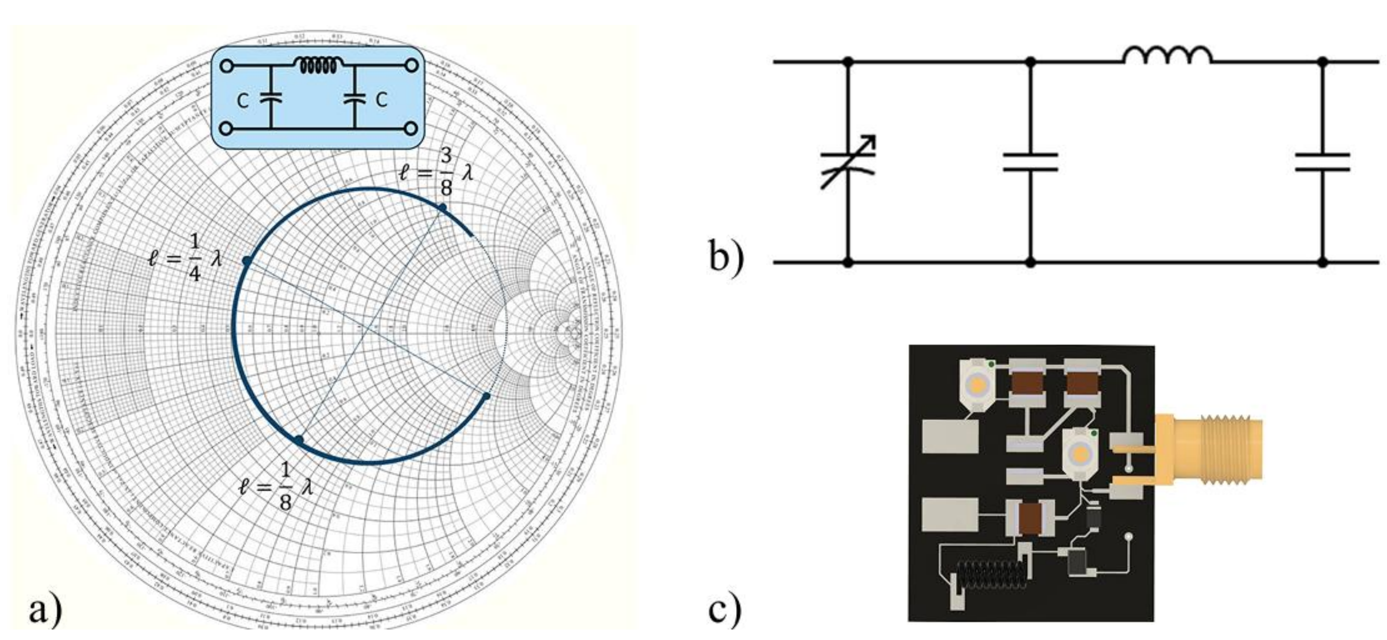

Fig. 2. π-Phase Shifter Design Elements: a) Impedance Analysis; b) Schematic; c) Printed Circuit Board

Flexible coils conform to the geometries of complex regions of interest. Eliminating space between the coil and skin results in a higher signal-to-noise (SNR) ratio and improved imaging. We assembled a receiver array and imaged a wrist using common clinical scans as shown in **Figure 3**. Our scans demonstrated a high SNR and improved imaging as fine anatomical structure became identifiable.

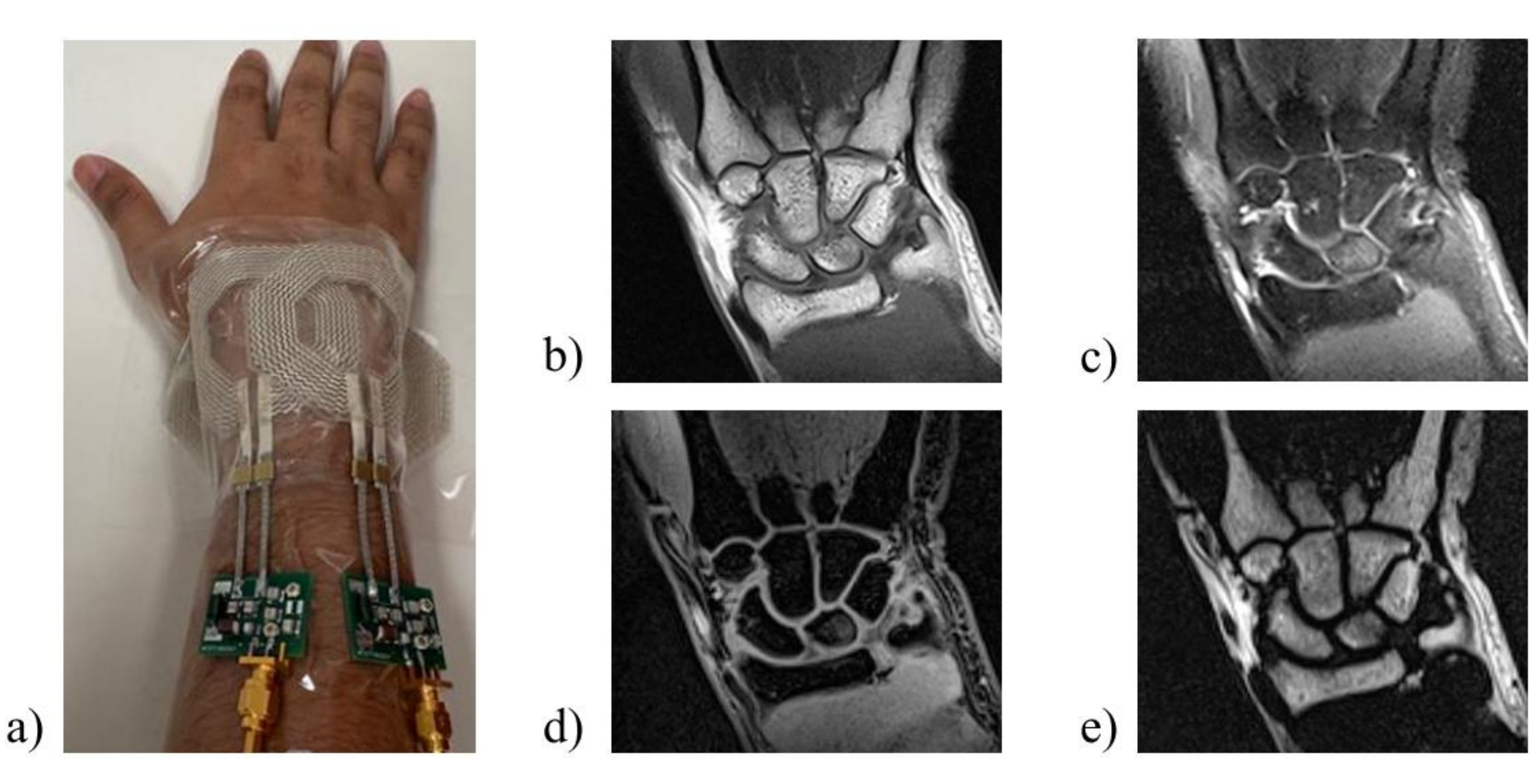

Fig. 3. a) Receiver Coil Array; b) T1 Weighted 2D GRE ; c) Proton Density Fat-Suppressed TSE; d) Dixon-Based Water; e) Dixon-Based Fat

III. MRI-Compatible Wearable Electrocardiogram

Traditional electrocardiograms (ECG) use leaded electrodes to acquire analog signals before processing. Our design aims to integrate the electrodes, analog front end, and microcontroller into a compact form factor—this not only offers wireless transmission but also minimizes interference from the magnetohydrodynamic (MHD) effect. As shown in **Figure 4**, our endgame intends to layer all components atop one another. Offering this compatibility expands the capabilities of surgeons utilizing MRI as an imaging method during surgery, as we can allow for safe, cardiac monitoring.

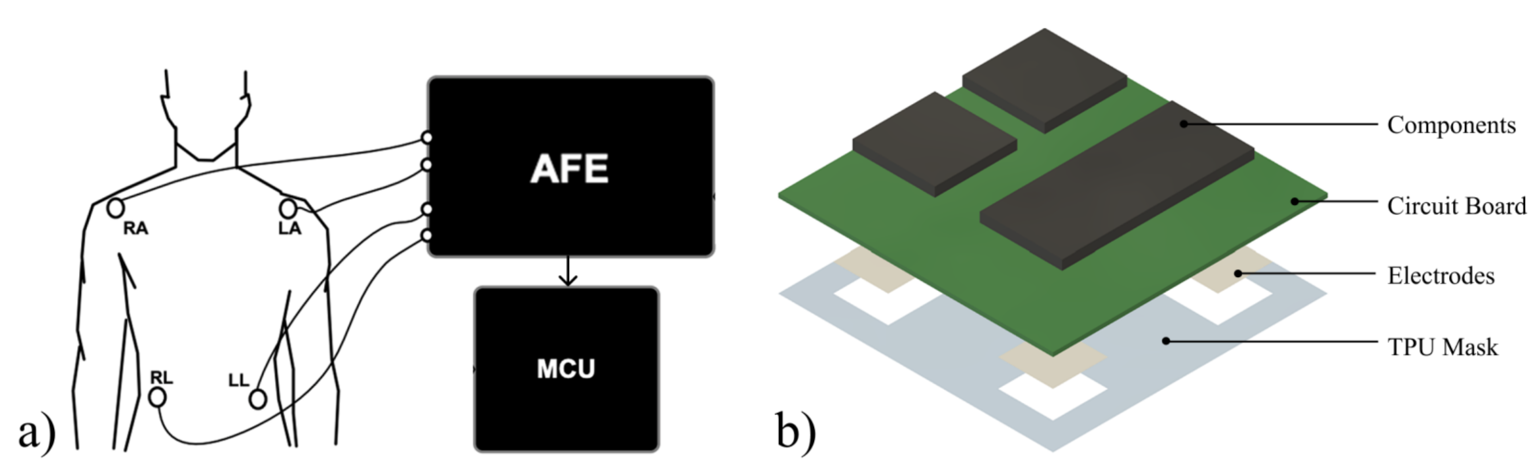

Fig. 4. Electrocardiogram Design: a) Traditional, Leaded; b) Wearable, Integrated

After initial prototyping, we tested our electrocardiogram in a non-MRI environment to ensure signal integrity of the PQRST sections, as shown in **Figure 5**. We acquired the expected ECG wave form and intend to test our data acquisition methods in an MRI environment. Through methods in shielding and signal processing, we hope to overcome any MHD interference.

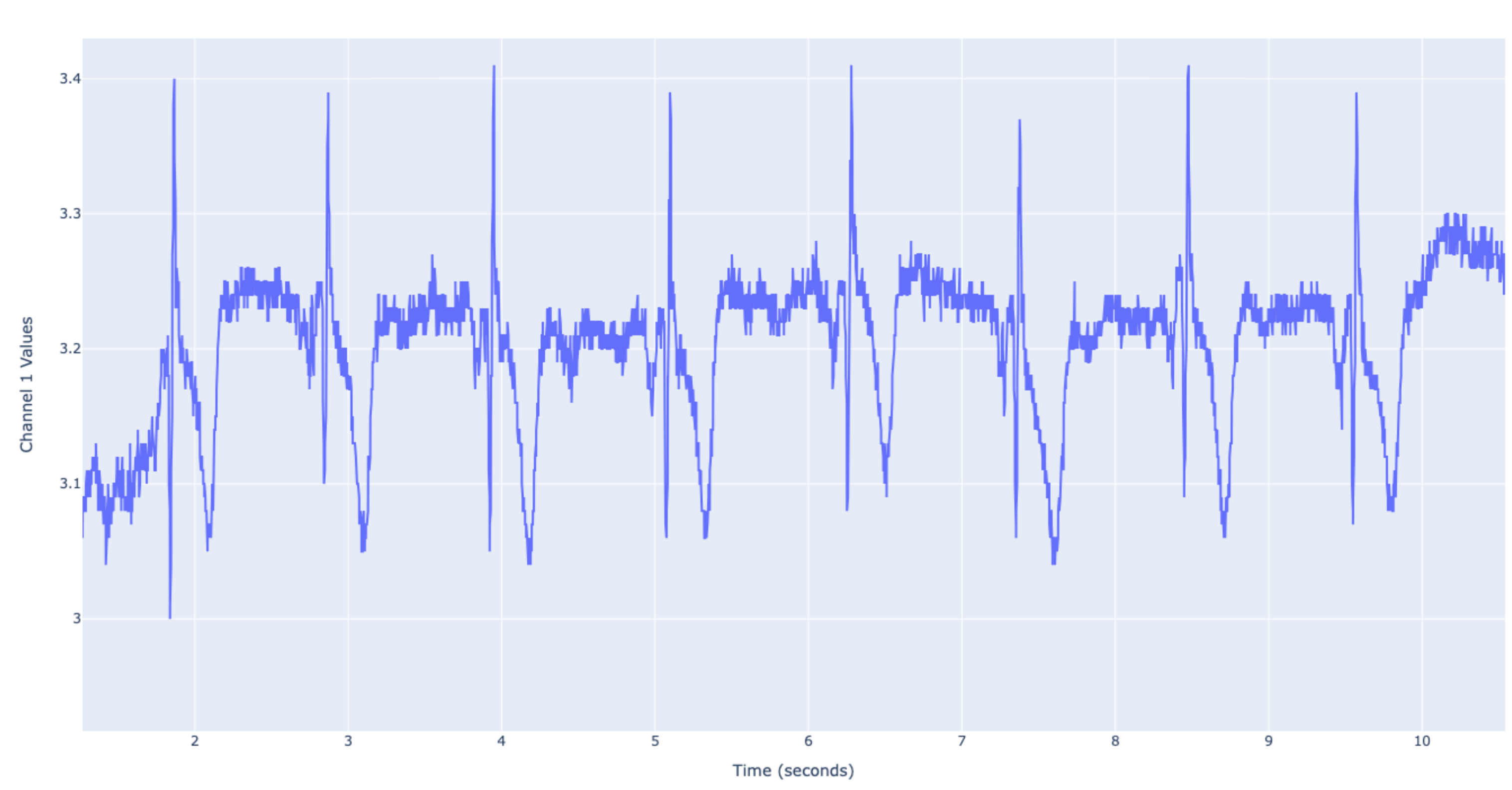

Fig. 5. Electrocardiogram Acquired Data

IV. Conclusion

In conclusion, our work demonstrates significant advancements in the development of MRI-compatible electronics, specifically in MRI coils and wearable electrocardiograms. Our development framework for both technologies is to fabricate current-carrying components with 3D-write and then interface them to a circuit board depending on applications, like tuning or analog-to-digital conversion. The usage of 3D-write technology allows for rapid iteration of flexible geometries for strain analysis. The MRI coils we've developed demonstrated improved flexibility that adheres to the unique geometries of the wrist and other complex regions—this allows for imaging of these regions during movement, offering improved diagnostic capabilities. While still nascent, our electrocardiogram developments have demonstrated repeatable data acquisitions on a small form-factor. We hope to capitalize on new methods of signal processing and hardware shielding to overcome any interference from the magnetohydrodynamic effect to offer compatibility in an MRI environment.

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