Wearable Radio-Frequency Sensors for Monitoring Human Body Kinematics

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***Abstract*—This is a project report for the 2019 IEEE MTT-S fellowship for medical applications summarizing the accomplished work. A new wearable technology is developed which has the potential to overcome shortcomings in the state-of-the-art, thereby promising unrestricted and real-time human body kinematics monitoring in uncontrived settings. Particularly, two variants are developed, keeping the elbow/knee joint kinematics as the main focus of the study: (a) Wrap-around coils in transverse configuration are capable of monitoring joint flexion/extension while being robust to rotation, and (b) Electrically Small Loop Antennas (ESLAs) arranged longitudinally can monitor both joint flexion/extension and rotation simultaneously.**

***Index Terms*—Electrically Small Loop Antennas (ESLAs), e-threads, joint flexion/extension and rotation, wearables, wrap-around coils.**

I. Introduction

MONITORING unrestricted human body kinematics in real-time and uncontrived environments is a vision that opens doors for multifaceted applications including, but not limited to, healthcare, sports, human-machine interfaces, gesture recognition, virtual reality, and biomedical research. State-of-the-art technologies can monitor motion but suffer from several limitations. Optical camera-based motion capture labs and their markerless version are accurate but restricted to contrived environments. Inertial Measurement Units (IMUs) break the lab boundaries but suffer from inherent drift leading to accumulated error over time. Electromagnetics based techniques such as radars, backscattering and Wi-Fi are generally used to classify different activities rather than monitoring particular types of motion (e.g., flexion/extension etc.), and generally require external set-ups that restricts them to contrived setting as well. Time-of-flight sensors that utilize ultra-wideband radio or ultrasonic transceivers are restricted by line-of-sight issues. Bending sensors that are worn directly on the joint restrict natural motion and have limited cycles of use. Abovementioned state-of-the-art is described in detail and referenced in [1-3]. These shortcomings are hindrance in realizing the aforementioned vision, thereby, providing strong motivation to develop a pertinent technology.

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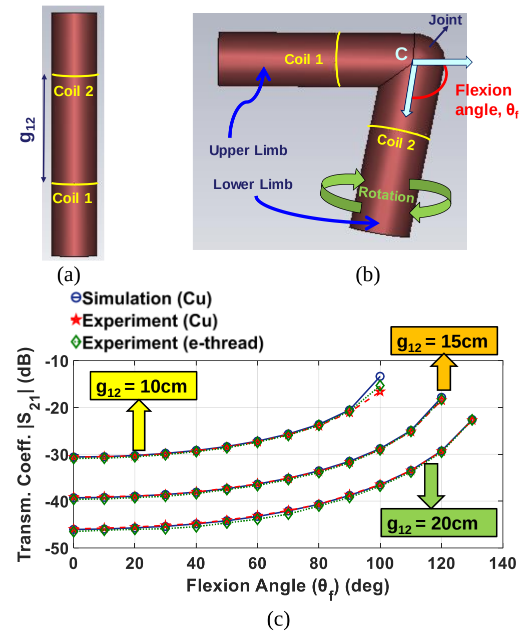
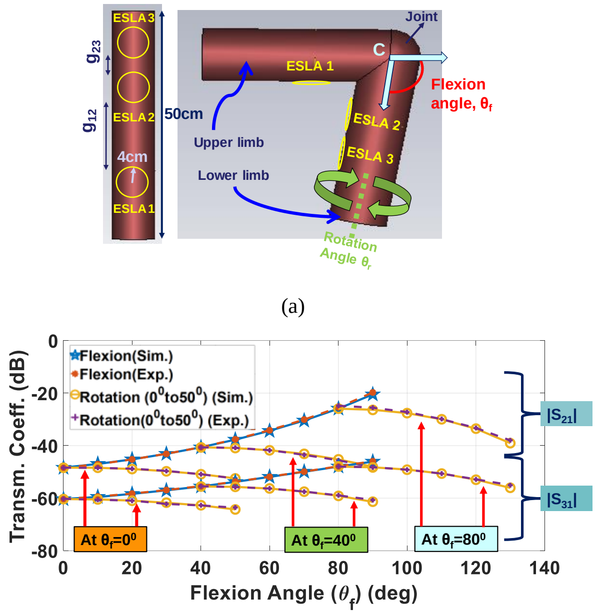


Fig. 1. Set-up showing: (a) extension, and (b) flexion of a cylindrical limb model for wrap-around coils with coil 1 as transmitter (Tx) and Coil 2 as receiver (Rx) [1] and corresponding (c) Experimental vs. simulation results for copper and e-thread coils at 34 MHz [1].

II. Project Outcomes

We have developed two variants of wearable radio frequency sensors to monitor arm/knee joint movements that operate around 34 MHz: (a) Wrap-around coils placed in transverse configuration (plane of the coil is transverse to the axis of the limb) [1] (Fig. 1(a, b)) are capable of monitoring joint flexion/extension while being robust to rotation, and (b) Electrically Small Loop Antennas (ESLAs) placed in longitudinal configuration (plane of the loop is parallel to the axis of the limb) [2] (Fig. 2(a)) to monitor both joint flexion/extension and rotation simultaneously.

To develop both of the aforementioned designs, the limb is approximated with a cylinder and the joint with a sphere, while 2/3 of muscle dielectric properties are used to emulate the average human tissue properties. In case of wrap-around coils (radius 4 cm), coil 1 (transmitter) and coil 2 (receiver) are placed symmetrically across the joint in a transverse configuration (Fig. 1 (a, b)). With joint flexion/extension, the coils misalign with respect to each, in turn causing change in the induced voltage (or transmission coefficient $|S_{21}|$) due to Faraday's law of induction. Thus, $|S_{21}|$ becomes a function of flexion angle (θ_f) and can be used to monitor flexion/extension.



(a)

(b)

Fig. 2. Set-up consisting of cylindrical limb and spherical joint made of 2/3 muscle with ESLA 1 used as transmitter (Tx), while ESLA 2 and ESLA 3 used as receivers (Rx) [2], along with corresponding (c) experimental vs. simulation results [2].

Simulation (with copper wire) and experimental (both copper wire and e-thread) results are shown in Fig. 1(c). This result clearly shows the feasibility of monitoring joint flexion/extension using wrap-around coils. Also, excellent agreement with e-threads demonstrates the feasibility of seamless integration on garments, thereby enabling the realization of our long-term vision. In addition, wrap-around coils are robust to rotation due to inherent symmetry involved in the configuration. In order to test the performance, a quantitative comparison was made against state-of-the-art IMUs. This showed that wrap-around coils perform equivalent or better for $\theta_f>20°$. Poor performance for smaller angles happens due to poor resolution or dynamic range of $|S_{21}|$ at lower angles (Fig. 1(c)). This can be improved by using the longitudinal ESLA design described next.

Two ESLAs (radius 4 cm) (see ESLA 1 and 2 of Fig. 2(a)) placed longitudinally across the joint are capable of monitoring both joint flexion/extension (θ_f) and rotation (θ_r) ($|S_{21}|$ of Fig. 2(b)) using the same operating principle as described for wrap-around coils. However, in this process, ambiguity arises due to the same $|S_{21}|$ values for different states of motion, i.e. (θ_{f1}, θ_{r1}) and (θ_{f2}, θ_{r2}) can correspond to the same value of $|S_{21}|$. To resolve this, a configuration with three ESLAs (Fig. 2(a)) is utilized, wherein a third ESLA (or second receiver) is added and placed asymmetrically across the joint with respect to the transmitter. The longitudinal configuration of two ESLAs is found to have significantly higher flexion dynamic range of $|S_{21}|$ across all θ_f (e.g., 18.8 dB improvement for g_{12}=10cm defined in Fig. 2(a)) thereby translating to highly improved flexion angle resolution as compared to the wrap-around coils. With three ESLAs, both flexion and rotation resolution of 2° (for g_{12}=10cm) and 0.4° (for g_{12}=3cm) is achieved.

A detailed frequency selection study was performed to decide the optimal region of operation and choice of coil/loop design. Specifically, the operation of wrap-around coils in antenna mode is detailed in [4]. Analysis in [1] shows that inductive mode is preferable compared to antenna mode of operation. Corresponding study for ESLAs is performed in [5]. Novelty related to experimental details for both configurations in [1], [2] also forms an important outcome of the project. Several design aspects for translation to real-world settings (such as radius of coils/loops and gap between the Tx and Rx (g_{12})) are analyzed in detail in [1], [2]. SAR_{1g} of 3.98 μW/Kg (for wrap-around coils) and 1.44 μW/Kg (for ESLAs) for an input power of -15 dBm was found for a study conducted on a multilayer limb model [1], [2]. This is well below the safety limit of 1.6 W/Kg set by FCC, thereby, making it highly safe for human use. Finally, wrap-around coils were successfully tested on dog's limbs, thereby, validating performance *in-vivo* and on anatomical geometries [6].

III. Career Plan, MTT-S Fellowship Impact and IMS Impression

I have always cherished academic environment and intend to join academia as a next step in my career. MTT-S fellowship has provided significant impetus in further strengthening my decision. This award was an important driver in boosting my confidence and motivation to perform best possible research that could positively impact the society. IMS-2019 was my first IMS conference, and, it has left remarkable impact on me. Although, as a student my experience is limited, but this was one of the biggest conferences that I have attended. The quality of work presented, student friendly and knowledge rich atmosphere, the complete management, and grandeur of exhibition hall were some of the things that impressed me most.

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