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Wearable Radio Frequency Loop Sensors for Monitoring Joint Kinematics

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Abstract

We report an emerging wearable sensor technology that relies on radio frequency (RF) loops to enable seamless monitoring of human body kinematics in uncontrived settings. Two variants of this technology are discussed that consist of loops placed transversally and longitudinally upon the limbs to monitor flexion-only and combined flexion and rotation, respectively. The reported approach overcomes shortcomings in state-of-the-art motion capture, offering unprecedented opportunities for the future of healthcare, sports, gaming, and more.

1 Introduction

Seamless monitoring of human body kinematics in uncontrived environments can benefit applications as diverse as healthcare, sports, human-machine interfaces, gesture recognition, virtual reality, and biomedical research [1]. However, state-of-the-art technologies (see Table I) used to monitor body motion suffer from several limitations [1], [2], and [3], hence restricting the aforementioned vision and necessitating the development of new technologies.

Specifically, optical camera-based motion capture labs and their markerless versions are accurate but restricted to contrived environments [4], [5]. Inertial Measurement Units (IMUs) can work outside laboratory settings but suffer from inherent drift [6]. Electromagnetics-based techniques, such as radars, backscattering and Wi-Fi, are typically used to classify activities instead of monitoring motion as a function of time and require bulky set-ups that restrict them to contrived settings [7]-[9]. Time-of-flight sensors that utilize ultra-wideband radio or ultrasonic transceivers are restricted by line-of-sight issues [10], [11]. Bending sensors that are worn directly on the joint restrict natural motion and have limited cycles of use [12].

To address these shortcomings in the state-of-the-art, we report a new technology that relies on wearable radio frequency (RF) loop sensors to monitor joint (e.g., elbow/knee) kinematics in the individual's natural environment. Two variants of this technology are available, namely (a) transverse configuration (TC) that enables monitoring of flexion while being robust to rotation [2], and (b) longitudinal configuration (LC) that enables monitoring of both flexion and rotation [3]. This paper provides an overview of these two sensor variants, their capabilities, and relevant recent developments.

2 Wearable Loop Sensor in Transverse Configuration (TC)

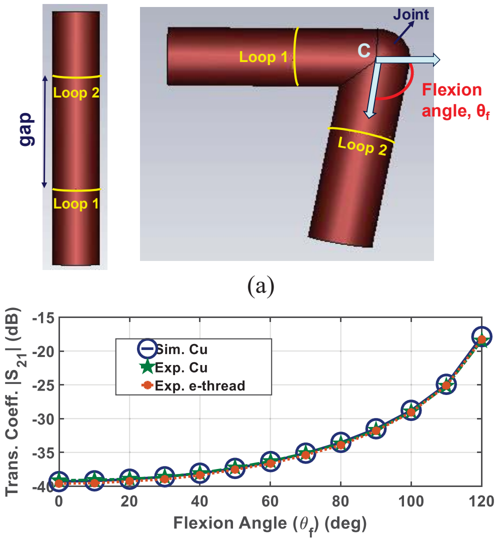
2.1 Design and Operating Principle

To form a wearable TC loop sensor, electrically small resonant loops are wrapped around the limbs (e.g., arm, leg) and placed symmetrically across the joint at a certain gap such that both are mutually coupled to each other (Fig. 1(a)) [2]. Here, the plane of the loops is transverse to the axis of the limb, hence the 'TC' naming selection. The operating frequency lies in the ~30-35 MHz RF range, such that the loops are coupled in the deep inductive regime.

Referring to Fig. 1(a), loop 1 acts as a transmitter and loop 2 as a receiver. As one limb (e.g., shank) bends/flexes with respect to the other limb (e.g., thigh), forming a flexion angle θ_f, the two loops misalign with respect to each other. This changes the voltage induced on the receiver according to Faraday's law of induction, thereby enabling the monitoring of movement information by means of the

TABLE I
COMPARISON OF STATE-OF-THE-ART WITH WEARABLE RF LOOP SENSORS FOR KINEMATICS MONITORING [2], [3]

	Camera Based	Inertial Measurement Units (IMUs)	Electromagnetics-Based	Time-of-Flight	Bending Sensors	Wearable RF Loop Sensors
Works in unconfined environment	No *(-)*	Yes *(+)*	No *(-)*	Yes *(+)*	Yes *(+)*	Yes *(+)*
Seamless	Yes *(+)*	No *(-)*	Yes *(+)*	No *(-)*	Yes *(+)*	Yes *(+)*
Unobtrusive	No *(-)*	No *(-)*	Yes *(+)*	No *(-)*	No *(-)*	Yes *(+)*
Insensitive to Line-of-Sight	No *(-)*	Yes *(+)*	No *(-)*	No *(-)*	Yes *(+)*	Yes *(+)*
Allows natural motion	Yes *(+)*	Yes *(+)*	Yes (+)	Yes *(+)*	No *(-)*	Yes *(+)*
Reliable vs. time	Yes *(+)*	No *(-)*	Yes *(+)*	Yes *(+)*	No *(-)*	Yes *(+)*
Injury-safe	No *(-)*	No *(-)*	Yes *(+)*	No *(-)*	Yes *(+)*	Yes *(+)*
Low logistics requirement	No *(-)*	Yes *(+)*	No *(-)*	Yes *(+)*	Yes *(+)*	Yes *(+)*



(a)

(b)

Figure 1. (a) Simulation set-up depicting wearable TC loop sensor upon a cylindrical limb that is straight and bent at flexion angle θ_f, and (b) corresponding simulation and experimental results [2].

receiver voltage or, equivalently, the transmission coefficient ($|S_{21}|$).

2.2 Simulation and *In Vitro* Experimental Results

As a proof-of-concept, the limb is approximated by a cylinder and the joint is approximated by a sphere, while 2/3 muscle properties are used to emulate the average dielectric properties of human tissues. Copper loops of 4 cm in radius are made resonant at 34 MHz using lumped capacitors and placed transversally upon the limb as shown in Fig. 1(a) [2]. Fig. 1(b) depicts the trend of $|S_{21}|$ obtained with respect to flexion angle at the resonance frequency, as obtained by simulation, *in vitro* experiments using copper wires, and *in vitro* experiments using conductive threads (e-threads). As seen, numerical and experimental results are in excellent agreement, confirming feasibility [2]. Notably, the trend obtained in Fig. 1(b) is a monotonically increasing curve, as desired to retrieve flexion angle without ambiguities. Concurrently, due to the inherent symmetry in the design, the sensor is robust to limb rotation, making it a reliable tool for joint flexion monitoring [2]. Comparison of our TC loop sensors vs. state-of-the-art IMU sensors show comparable or significantly better performance for $\theta_f > 20°$ [2].

2.3 *In Vivo* Experimental Results

To validate our TC sensors *in vivo*, an experiment is performed upon a dog's knee joint that is manually flexed from $\theta_f = 30°$ to $110°$ [13]. TC loops operating at 31 MHz are designed, integrated on a knee brace, and connected to a network analyzer to capture the $|S_{21}|$. Measurement results are shown in Fig. 2 [13], confirming feasibility for (a) living beings (or *in vivo*), (b) transmitter and receiver of unequal radii, and (c) loops that take the shape of the underlying anatomical geometry. This empowers *in vivo* testing on humans as the next step.

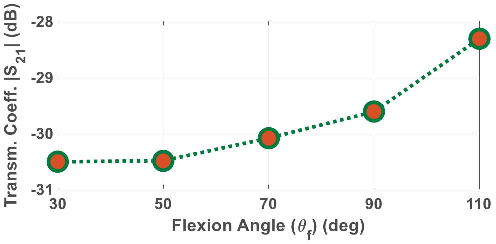
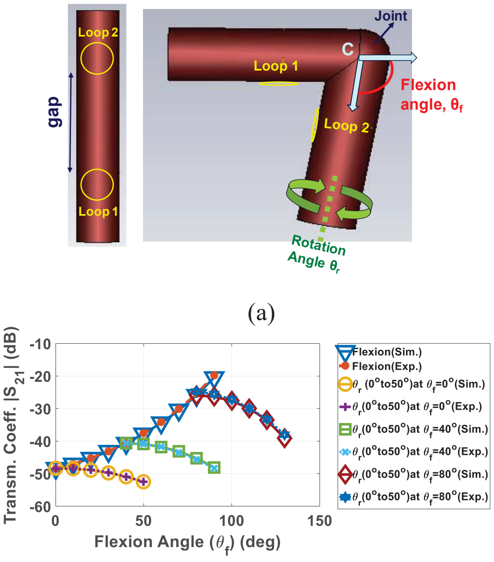


Figure 2. Experimental results showing monitoring of dog's knee joint flexion using wearable TC loop sensor operating at 31 MHz [13].

3 Wearable Loop Sensor in Longitudinal Configuration (LC)

The design and operating principle of LC sensors are similar to TC, yet loops are now placed in a longitudinal fashion instead of transverse, i.e., the plane of the loop is along the axis of the limb (Fig. 3(a)) [3]. This longitudinal placement of loops brings forward two pronged benefits. Specifically, LC sensors (a) allow for simultaneous monitoring of both flexion and rotation which is not possible with TC sensors (achieved by breaking the inherent symmetry present in the design of TC sensors), and (b) provide significantly improved angular resolution, especially at lower angles, as compared to TC sensors [3].



(a)

(b)

Figure 3. (a) Simulation set-up depicting wearable LC loop sensor when limb is straight and bent at flexion angle θ_f, and (b) corresponding simulation and experimental results [3].

Simulation and *in vitro* experimental results are depicted in Fig. 3(b) [3]. As a proof-of-concept, results include the flexion curve as well as indicative rotation curves at three different flexion angles of $\theta_f = 0°$, 40°, and 80°. Notably, excellent agreement is achieved which confirms the practical feasibility of LC sensors. Of course, changes in the design are possible to cater to different application requirements [3].

Nevertheless, by carefully observing Fig. 3(b), one can notice that same $|S_{21}|$ values may represent various different states of motion. This ambiguity issue in the LC sensor can be resolved by adding a third loop (or a second receiver) placed adjacent to the first receiver at a small gap. By referring to this loop as loop 3, asymmetric flexion curves are produced for $|S_{21}|$ and $|S_{31}|$, which can be utilized to resolve ambiguity. It is shown in [3] that a two-loop configuration is sufficient for an angular resolution greater than or equal to 10°. When a third loop is added, ambiguity is resolved and resolution can go down to as low as 2°. This is, however, not limiting, and the resolution can be improved further, for both the two- and three-loop configurations by designing the sensor appropriately [3].

4 Conclusion

An overview of a new class of wearable RF (~ 30-35 MHz) loop-based sensors was presented that enables seamless monitoring of joint kinematics while overcoming shortcomings in the state-of-the-art. Two different variants of the sensor were discussed, namely transverse and longitudinal configurations (TC and LC). *In vitro* simulation and experimental results demonstrated that TC sensors can monitor joint flexion reliably, while LC sensors can simultaneously monitor flexion and rotation while also achieving significant improvement in angular resolution. Prototypes of the TC sensor realized on e-threads exhibited similar performance to their copper counterparts, thereby demonstrating the feasibility of translating the design on textiles. Furthermore, in comparison with state-of-the-art IMU sensors, the TC sensor was shown to achieve equivalent or better performance for $\theta_f > 20°$. Concurrently, our approach is much more unobtrusive as compared to IMUs and does not suffer from integration drift. Finally, *in vivo* testing on dogs further confirmed the feasibility of sensor operation on living beings and under realistic scenarios.

In the future, these sensors will be tested on anatomical tissue models, translated on conductive textiles and tested *in vivo* on human subjects.

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