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Design and Verification of IR-UWB Localisation Sensor Node with Cavity-Backed Textile Antenna

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Abstract

This paper handles the design and verification of a localisation sensor with a cavity-backed slot antenna. The sensor node uses a Decawave DW1000 chipset, together with a basic sensor, a microcontroller and a flash memory card. It is designed on a mechanically flexible Printed Circuit Board (PCB), where component edges and vias are aligned forming rigid lines. As antenna a Substrate Integrated Waveguide (SIW) design is proposed: a cavity-backed slot antenna combining vulcanised rubber foam and electrotextile. Impulse-Radio Ultra-Wideband (IR-UWB) localisation is analysed by the pulse deformation in the System Fidelity Factor (SFF) and the phase shift in the Distance Estimation Error (DEE). On-body measurements show that everything works fine.

1 Introduction

Electronic tools are nowadays integrated in a collection of everyday objects, connected to the internet and known as Internet of Things (IoT). Its success is directly related to the proximity to and interaction ability with its users. A promising candidate technology can be the use of Smart Fabrics and Interactive Textiles (SFIT), which essentially involves the enhancement of functionalities offered by textile and by the integration of electronics. In particular, user-worn textiles are in pole position to collect on-body sensor data, to pass on information to the user and to convey the user's needs or wishes to actors in its environment.

However, numerous challenges remain before the smart textile industry can perform the scale-up necessary for a market breakthrough. First of all, keeping consumer adoption and ease of use in mind, such systems should be integrated in the garment in an unobtrusive and comfortable way. They should be mechanically flexible, avoiding stiff segments as much as possible. Mass production requires steps that are cheap and machinable and offer reliable and accurate results. The end products should be washable, robust and resilient when body-deployed. Smart wearable systems should also be power-efficient, since batteries take up a large portion of a system's mass and space budget. Replacing batteries is difficult or sometimes impossible and recharging should be kept to a minimum to improve ease of use. Finally, an antenna topology should be chosen, exhibiting a low coupling with the human body and experiencing significantly less effect from the deployment position or body morphology.

This paper describes the implementation of an Impulse-Radio Ultra-Wideband (IR-UWB) localisation sensor with a cavity-backed textile slot antenna, designed in Substrate Integrated Waveguide (SIW) technology. Both the antenna and the supporting electronics are made as mechanically flexible as possible. In Section 2 the design of the IR-UWB localisation sensor node is described. In Section 3, the design and manufacturing of a mechanically flexible, all-textile cavity-backed slot antenna is handled. The System Fidelity Factor (SFF), the Distance Estimation Error (DEE) and on-body measurements are detailed in Section 4. The paper ends with a conclusion in Section 5.

2 Design of the sensor node

The IR-UWB localisation sensor node is realised on a mechanically flexible polyimide substrate, taking into account the same dimensions of the cavity-backed slot antenna (see Section 3). It allows for unobtrusive and wearable integration of the system into body-worn textiles. The electric scheme is shown in Figure 1. The main component is the Decawave DW1000 localisation IC, also hosting a built-in transceiver. It is fully compliant with the IEEE 802.15.4-2011 standard. A basic sensor such as the Bosch Sensortec BME280 temperature, air pressure and relative humidity sensor is integrated in the board. Both are controlled by an ultra-low power Silicon Labs C8051F921 microcontroller. An Adesto AT45DB321E 4MB flash memory card is included, allowing application-dependent storage of sensor data. All communication between the components occurs via the SPI protocol. Since the use of bulky connectors conflicts with the wearability constraints, a Tag Connect landing pad has been provided for debugging. The RF output of the DW1000 is connected via a trimmed Multi-Contact 42.0001 brass-gold pin with a diameter of 1 mm. The antenna (see Section 3) and the circuit's feed pin structure are co-optimised to provide a 1.8 mm diameter ground clearance, together with an aperture in the backplane of the antenna cavity. Then, the probe feed structure is realised by fitting the feed pin through the middle of this hole, after which the antenna is completed by soldering the pin's other end to the antenna top plane.

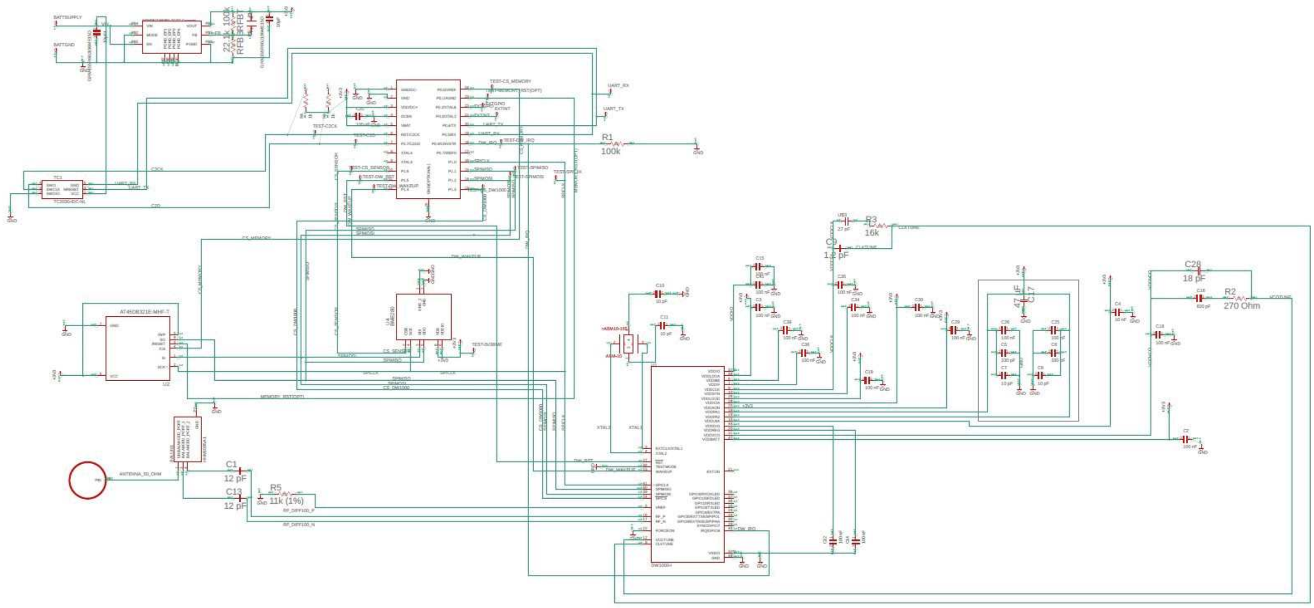

Figure 1. Schematic of the PCB-design.

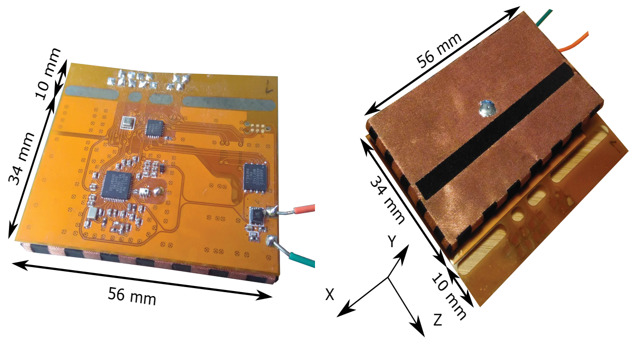

Figure 2. Left: final PCB with on the back the cavity-backed slot antenna. Right: cavity-backed slot antenna.

When designing a mechanically flexible Printed Circuit Board (PCB), care must be taken to distribute the mechanical stress applied to the solder seams and copper due to bending. The individual stiffness of isolated vias and soldering joints is combined by aligning vias and component edges to form several rigid lines. If sufficient well-positioned bending spaces are implemented in between those rigid lines, the PCB concentrates its bending along those directions. Bending can of course induce mechanical stress concentrated in inner angles of the copper planes and in the transitions between signal lines and vias. Therefore, gradual bends in copper sheets are preferred and the transition between signal lines and vias should be realised in a gradual droplet-like shape. Also, signal lines need to bend smoothly instead of with sharp 90° or 45° angles [1]. The connection between the ground plane and the antenna backside is realised by Electroless Nickel Immersion Gold (ENIG) surface plating, patterned in a honeycomb structure to maintain mechanical flexibility while keeping a sufficient electrical contact with the underlying electrotextile.

3 Cavity-backed slot antenna

In this section, the design and fabrication method for a mechanically flexible, all-textile cavity-baked slot antenna is handled. It is of use for localisation through Impulse-Radio Ultra-Wideband (IR-UWB) in Channel 2 and Channel 3 of the IEEE802.15.4a standard (3744 MHz - 4243.2 MHz and 4243.2 MHz - 4742.4 MHz, respectively). The antenna is based on the coupled half-mode cavity-backed slot antenna design in [2], where mode bifurcation is used to increase the antenna's bandwidth ([3]). Two SIW half-mode cavities are designed with slightly different resonance frequencies and the open ends are placed in close proximity, resulting in a strong mutual coupling.

In order to fabricate a mechanically flexible antenna, the following procedure is proposed [4]. Firstly, both the 4 mm thick vulcanised rubber foam and the electrotextile with laminated thermally activated sheet adhesive are laser cut into their respective shapes. The one single piece electrotextile is folded around the vulcanised rubber foam in a later step, thereby significantly reducing potential misalignments of the top and bottom planes. Next, after alignment, the vulcanised rubber foam and the electrotextile are glued together by a textile heat transfer press, activating the glue. Then, the rest of electrotextile is wrapped around the substrate, forming the final cavity as shown in Figure 2. Note that the spaced apertures in the vertical walls of the cavity create a rectangular SIW cavity.

4 Results

This antenna topology exhibits a directive radiation pattern oriented away from the human body, with a measured front-to-back ratio (FTBR) higher than 11 dB within the IEEE 802.15.4-2011 Channels 2 and 3. These results also demonstrate that this antenna topology experiences low coupling with the human body, thereby reducing the wearer's Specific Absorption Rate (SAR) and limiting the influence of human body proximity on the radiation pattern and impedance matching of the antenna. The measured impedance matching and radiation pattern indeed remain stable in diverse body deployment scenarios, such as when deployed on the torso or upper right arm of a test person or when the antenna has been bent in free space over bending radii commonly found on the human body [2]. Therefore it can be concluded that coupling with the human body is indeed low, as can be expected from the cavity topology.

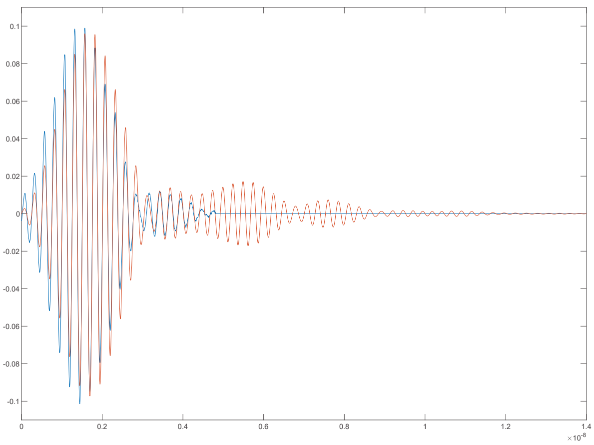

Figure 3. Normalised pulse at the transmit antenna (blue) compared with normalised pulse at the receiver antenna (red).

To qualify for body-worn positioning, one of the antenna's orientation-specific parameters is the pulse deformation, impeding proper and accurate signal reception. Hence, this pulse deformation should be minimised. It is analysed by means of the System Fidelity Factor (SFF) [5], defined as:

$$\mathrm{SFF} = \max_t \left| \frac{\int_{t_0}^{t_n} T_s(\tau) R_s(\tau + t) d\tau}{\sqrt{\int_{t_0}^{t_n} T_s^2(\tau) d\tau \int_{t_0}^{t_n} R_s^2(\tau) d\tau}} \right| \qquad (1)$$

where $T_s(t)$ represents the pulse at the transmit antenna's port and R_s(t) at the receive antenna's port. The latter is obtained by convolving $T_s(t)$ with the impulse response of the system composed by two prototypes of the aforementioned antenna and combined with the free space channel in between them. The higher the SFF is, the lower the pulse deformation will be. As such, the antenna is analysed in a complete transmit-receive antenna system. The all-textile IR-UWB antenna is used as a transmit and as a receive antenna. As an input pulse, the default output pulse of the Decawave DW1000 chipset when operating in Channel 2 is used. In Figure 3, the input pulse is plotted in blue and the output pulse in red.

While the transmit antenna is transmitting along broadside, the receive antenna is rotated in its E- and H-plane. The

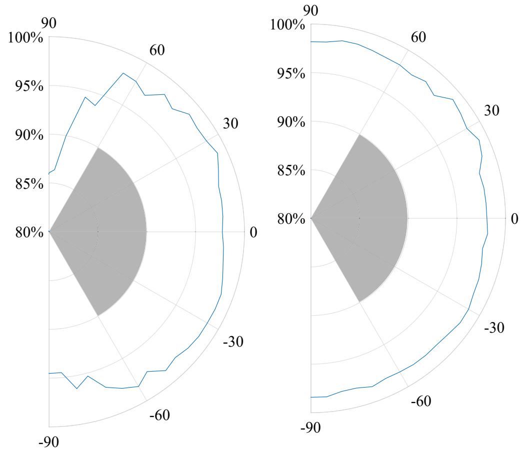

Figure 4. Measured system fidelity factor (SFF) as function of the angle. Left: azimuth plane (XY-plane). Right: elevation plane (YZ-plane). As reference, the SFF > 90% goal is marked in grey.

obtained SFF is displayed in Figure 4. We can conclude that the SFF is better than 90% for all relevant orientations. As such, the pulse distortion due to the antenna characteristics is small enough for localisation algorithms to provide accurate location estimations.

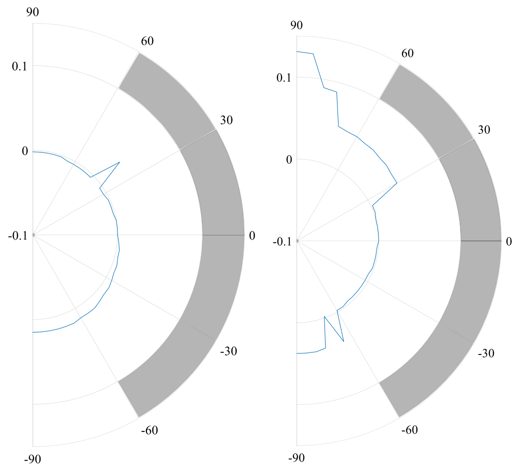

Figure 5. Distance estimation error. Left: E-plane. Right: E-plane. As a reference, the |DEE| < 0.1 m goal is marked in grey.

Another important parameter for body-worn positioning is the distance estimation error (DEE), determined by the time lag at which the SFF becomes maximal [6]. The DEE is visualised in Figure 5. As can be seen, it is lower than 0.1 m, implying that the localisation error introduced by the antenna remains smaller than the error caused by commercial localisation ICs such as the DW1000, thereby acknowledging the suitability of the antenna for IR-UWB localisation purposes.

The integration of a comprehensive, mechanically flexible sensor node on the backside of the antenna, acts as a proof

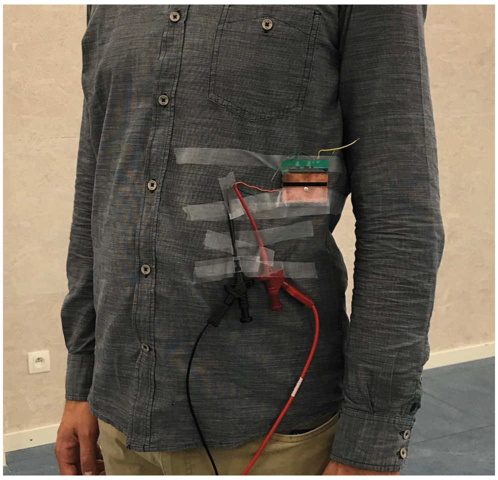

Figure 6. Test subject outfitted with the sensor node on the torso, externally powered for measurement purposes.

Table 1. Percentage of transmitted packets received by the two wall-mounted anchor nodes located in the opposite direction of the textile antenna's broadside rotation.

	Right		Left	
	Top	Bottom	Top	Bottom
45°	21,92%	97,26%	0,00%	12,50%
135°	90,91%	98,70%	0,00%	0,00%
225°	0,00%	0,00%	0,00%	96,51%
315°	36,53%	97,62%	0,00%	32,92%

of concept for the implementation of IR-UWB localisation electronics. A body-worn localisation system should be able to provide adequate quality-of-service, regardless of the user's orientation with respect to the surrounding localisation infrastructure. Not all anchor positions can be reached simultaneously by the same antenna. Therefore, multiple antenna positions on the wearer's body should be used, as every direction around the user's body must be serviced by at least one body-worn antenna element. To investigate this, a system consisting of multiple wearable sensor nodes has been deployed on 4 different orientations around the waist of a male test person with a size of 1.90 m and a mass of 85 kg: 45°, 135°, 225° and 315°. To facilitate testing, the system is attached on the torso, as shown in Figure 6, allowing it to be shifted around the test person between the different body deployment locations under study.

In Table 1, for all investigated body deployment orientations, the fraction of the amount packets received on the two wall-mounted anchor nodes located at an azimuthal deflection of ±67° with respect to the textile antenna's broadside direction, is displayed. To qualify a body deployment position, the connectivity between the anchor nodes and the sensor system should be reliable for all investigated elevation angles. However, due to the directive radiation pattern and the body shadowing effect, one single sensor node is unable to provide localisation coverage in all directions around the user.

5 Conclusion

In a first part of this paper the design of an IR-UWB localisation sensor node with cavity-backed textile antenna is discussed. The sensor node is realised on a mechanically flexible PCB, where rigid lines are formed by aligning vias and component edges of amongst others a Decawave DW1000 chipset, a microcontroller and a flash memory card. It is combined with a cavity-backed textile slot antenna. The SIW cavity in vulcanised rubber foam is surrounded by electrotextile, resulting in a FTBR higher than 11 dB. The pulse deformation is quantified by the SFF, which is larger than the 90% commonly required for localisation. The antenna's DEE is lower than 0.1 m, implying that the localisation error introduced by the antenna remains smaller than the error caused by commercial localisation ICs such as the DW1000. On-body measurements show that everything works fine and it can be concluded that this sensor system is suitable for body-worn localisation through IR-UWB and that it acts as a proof-of-concept for the integration of electronics into body-worn textiles.

6 Acknowledgements

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