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EXPANDING THE HORIZONS OF WIRELESS SENSING:

Sensing and localizing contact forces with signal reflections

Excerpted from "WiForce: Wireless Sensing and Localization of Contact Forces on a Space Continuum" from *Proceedings of the 18th USENIX Symposium on Networked Systems Design and Implementation (NSDI '21)* with permission. https://www.usenix.org/conference/nsdi21/presentation/gupta

All interactions of objects, humans, and machines with the physical world are via contact forces. For instance, objects placed on a table exert their gravitational forces, and the contact interactions via our hands/feet are guided by the sense of contact force felt by our skin. Thus, the ability to sense the contact forces can allow us to measure all these ubiquitous interactions, enabling a myriad of applications. Furthermore, force sensors are a critical requirement for safer surgeries, which require measuring complex contact forces experienced as a surgical instrument interacts with the surrounding tissues during the surgical procedure. However, with currently available discrete point-force sensors, which require a battery to sense the forces and communicate the readings wirelessly, these ubiquitous sensing and surgical sensing applications are not practical. This motivates the development of new force sensors that can sense, and communicate wirelessly without consuming significant power to enable a battery-free design. In this magazine article, we present *WiForce*, a low-power wireless force sensor utilizing a joint sensing-communication paradigm. That is, instead of having separate sensing and communication blocks, WiForce directly transduces the force measurements onto variations in wireless signals reflecting WiForce from the sensor. This novel trans-duction mechanism also allows WiForce to generalize easily to a length continuum, where we can detect as well as localize forces acting on the continuum. We fabricate and test our sensor prototype in different scenarios, including testing beneath a tissue phantom, and obtain sub-N sensing and sub-mm localizing accuracies (0.34 N and 0.6 mm, respectively).

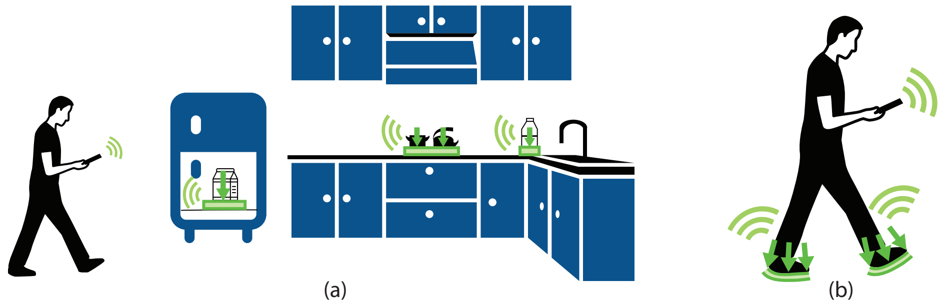

FIGURE 1. Forces (green arrows) are exerted by (a) various objects located ubiquitously in the environment. (b) As well as our contact interactions, as an example, feet impact forces while walking.

Over the last few years, there has been a significant push to utilize wireless signals not only for communicating information but also for sensing the environment and human interactions. Today, we have wireless sensing capabilities to sense the ambient temperature of the environment, vibrations, hand gestures, and even breathing rate [1-3]. Force is another such physical phenomenon that enables richer information about both the environment, as well as human interactions. Any object placed on a table exerts the gravitational force corresponding to its weight, and most of our touch interactions would be incomplete without our rich sense of contact force via numerous mechanoreceptors present in the skin. However, to date, the rich information that force can give about our ubiquitous environment and the touch interactions have not been captured by wireless sensors.

Wireless force sensing can enable numerous ubiquitous sensing and human-computer interaction (HCI) applications. We can deploy a force sensor at the bottom of water bottles, milk cans, and other objects located ubiquitously in our environment to estimate the weight of their contents. Then, by wirelessly communicating these sensor readings to user's smartphones, using a standard technology such as BLE/Wi-Fi, we can notify the users to maintain healthy hydration, or if the user is out of milk (Figure 1a). However, to support so many of these everyday objects in a practical way without requiring frequent battery replacement or charging, these sensors must be sufficiently low-powered to enable a passive, battery-free operation. Wireless passive force sensors would not only make these current applications practical but would also enable newer applications. For example, these sensors can then be mounted in unusual locations due to their wire-free, battery-free operation, like beneath a shoe sole to help estimate the landing foot force while walking/running (Figure 1b), paving the way ahead for interesting HCI and health monitoring use-cases of force sensing.

Another such emerging application for these low-powered force sensors lies in the field of minimally invasive surgeries, where the surgeons have to operate through a small opening in the body (Figure 2). Here, the surgeon does not get a direct measurement of how much force the surgical instrument is applying to the body tissues, which can lead to potentially unsafe surgeries [4]. The lack of force feedback in today's surgical settings also hampers the feasibility of upcoming robotic surgeries, which require force sensing to control and guide the robot [5]. In these applications, wireless low-powered force sensing becomes a must requirement.

These surgical instruments and robots can not afford to have a bunch of wires to sense forces, since space is at a premium. At the same time, the prospects of moving to a traditional wireless solution by transmitting the sensor data wirelessly, which would require a battery, pose a risk of introducing hazardous materials inside the body. The problem is further exacerbated as it is desired to not only estimate force at a particular sensor mounting point, but to estimate individual forces across the continuum of the instrument (Figure 2), and localize where these forces are acting along the surgical instrument. With today's technologies, it is unfeasible to attempt this application. The wired MEMS discrete force sensors would need to be deployed by the hundreds in an array estimate forces along the continuum. Now, to wirelessly communicate these sensor array readings, we would need to use a technology like BLE, which would demand a battery to transmit these sensor readings. Even if the wireless technology is somehow made low-powered, due to having multiple sensors with a single communication block, the wiring setup of these hundreds of sensors to a wireless transmission unit itself would quickly exacerbate the space constraints posed by these surgical applications.

Breaking away from traditional sensing methods, which have different sensing and communication blocks (eg. MEMS force sensors + BLE communication modules), WiForce [6] unifies these into a joint sensing and communication paradigm that is sufficiently low-powered and can be made potentially battery-less as well. Instead of using hundreds of sensors deployed across the length, WiForce designs a single continuous force-sensitive strip that transduces force magnitude and location onto variations in the reflected signal. These variations in reflected signals translate to variations in the wireless channel measured by any externally located device. Thus, the WiForce sensor can be read by any appropriate waveform for channel sounding, like FMCW for radar sensing and OFDM for Wi-Fi.

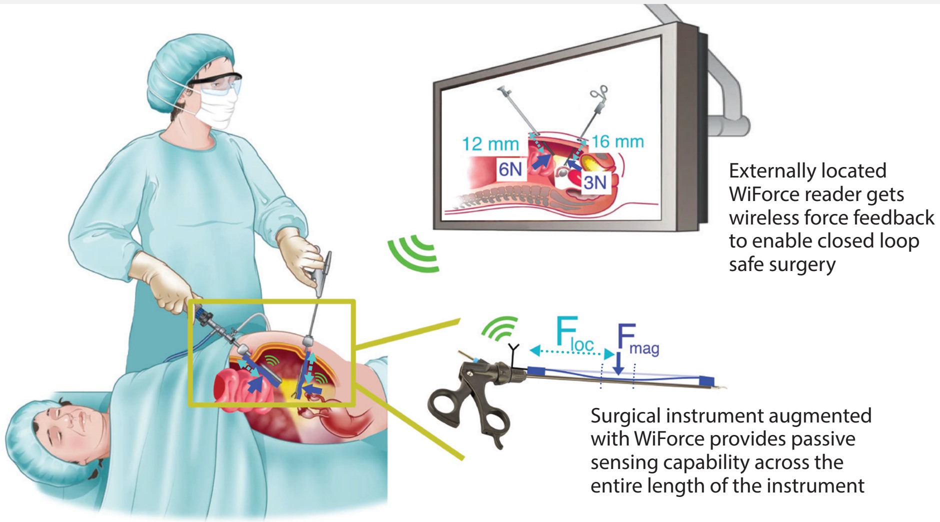

FIGURE 2. Passive wireless force sensing can help the surgeons perform safer minimally invasive surgeries, by feeding back the contact locations and force.

DESIGN

In this section, we will first go over the WiForce transduction mechanism that enables a joint communication and sensing approach for sensing and localizing force over a continuum. Next, we will briefly describe how this sensing approach is robust to environmental factors and can generalize easily to read from multiple sensors simultaneously.

A joint communication-sensing paradigm to sense forces

The traditional approach to sense forces has been to utilize transduction mechanisms, which lead to voltage variations when forces are applied onto the sensors [7-9]. To sense voltage variations wirelessly, we would require power-hungry electronics like ADCs to digitize the sensor data and digital communication blocks to transmit the data over a wireless link (Figure 3a). This approach of interfacing sensing and communication blocks with ADCs exacerbates the power and space requirements for enabling various applications with passive wireless force sensing.

Thus, moving away from this traditional approach, WiForce designs a transduction mechanism that utilizes a joint sensing and communication paradigm over a length continuum to cut down on power and space requirements drastically. The key insight here is to transduce forces acting on the length continuum, onto the reflected signal phases instead of voltages. Unlike voltages, phase is an inherent property of radio signals and can be easily sensed wirelessly, without the need of interfacing ADCs and separate communication blocks.

To enable this force to phase transduction mechanism, we design a sensor to be a microstrip line augmented with a mechanical top beam (Figure 3b) to act as our length continuum. A force acting on this length continuum would make the mechanical beam deform and bend, and it comes into contact with the bottom ground trace. This shorts the microstrip line with lengths L1 and L2 from either end of the sensor (Fig. 3c). These two shorting lengths capture the extent of the bending effect created by forces acting at a certain location on the sensor. Thus, by utilizing a mechanical beam bending sensor model, we can estimate the force magnitude and force location by estimating these two lengths L1, L2. Now,

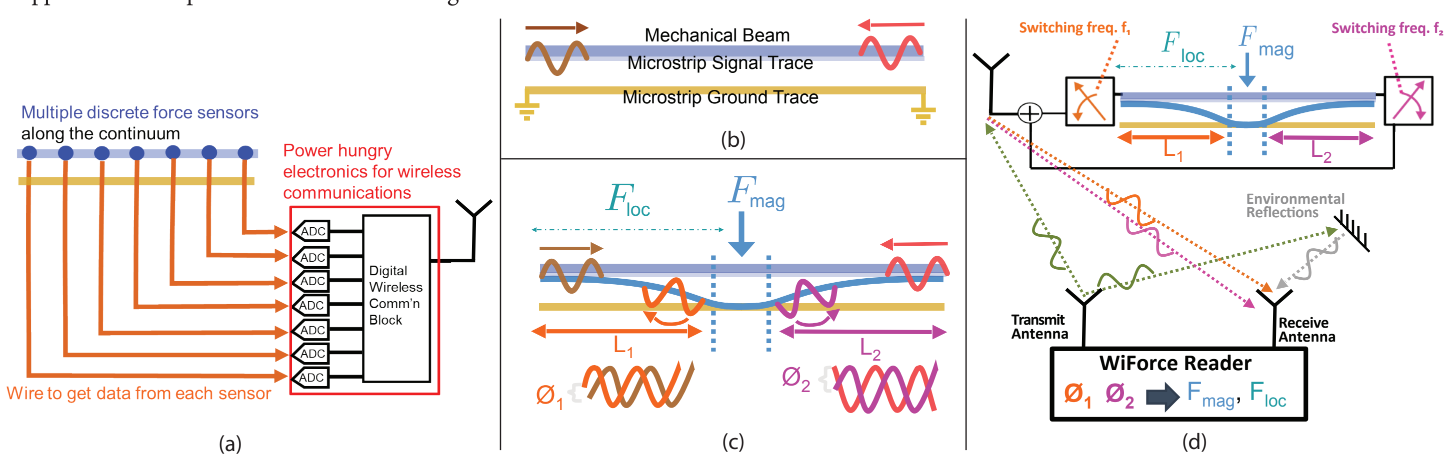

FIGURE 3. (a) Traditional method to enable wireless sensing and localization of forces on a continuum. (b) WiForce sensor design consisting a mechanical beam sensing continuum and a microstrip line to allow RF signal propagation. (c) Due to forces on the mechanical beam, the sensor bends, creating signal reflections due to signal-ground shorting with contact lengths L1, L2 , leading to phase shifts Ø1, Ø2 in the signal reflections. (d) The reflected signal is modulated by RF switches goggling at different frequencies, allowing the reader to estimate Ø1, Ø2 and wirelessly sense and localize the force that caused these phase shifts.

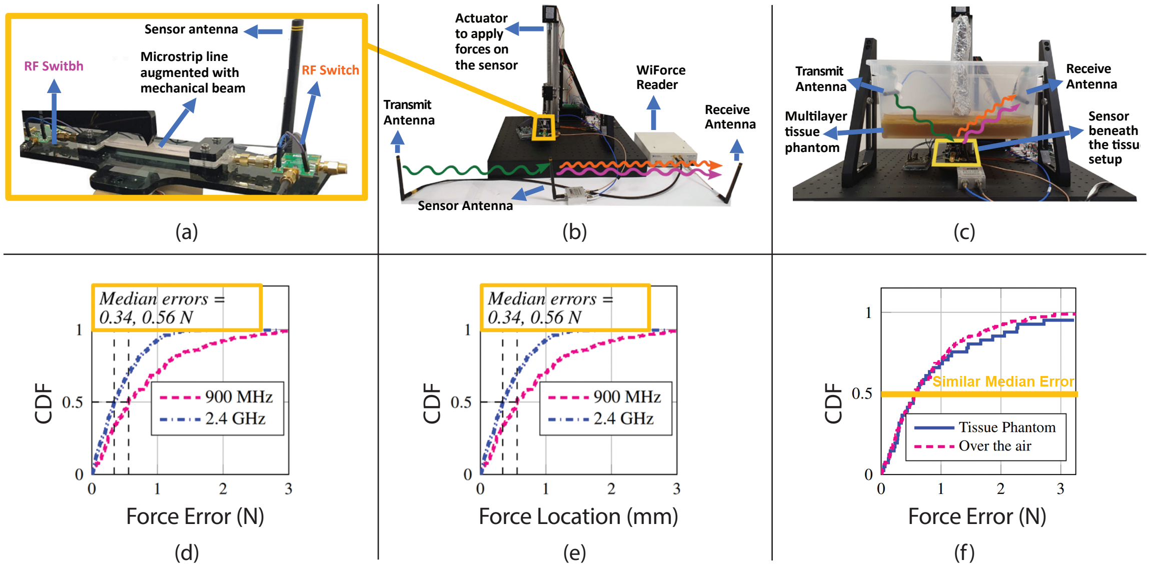

FIGURE 4. WiForce Experiment Setups and Benchmarking results: (a) WiForce Sensor Prototype. (b) Over the air evaluation platform. (c) Tissue phantom evaluation setup. (d) WiForce's force sensing performance. (e) WiForce's force localization performance (f) WiForce's robustness to in-body propagation.

lengths and phases are linked intrinscally, as signals accumulate phase changes proportional to how far they travel before getting shorted. Hence, computing phase changes in the reflected signals from boththe sensor ends is equivalent to sensing these shorting lengths. Thus, WiForce creates a sensor model, which estimates the force magnitude, as well as its location on the length continuum of the mechanical beam, based on the changes in signal phase by using just a single sensor over the length continuum.

ROBUST, MULTI-SENSOR SCALABLE WAY OF SENSING FORCES WIRELESSLY

To sense these phase changes wirelessly, WiForce reader mimics a monostatic radar with a transmit and receive antenna. The reader first transmits a signal, which is received at both the sensor ends, gets shorted, and reflects back towards the reader. In addition to the reflections originating from the sensor, there is a myriad of environmental reflections as well and the reader receives a combined sum of all these reflections. To help the reader identify the reflections originating from the sensor from the environmental clutter, we augment our sensor design with low-power RF switches that toggle on-off at non-conflicting frequencies (Figure 3d). This on-off toggling creates distinct frequency shifts in the reflections originating from the sensor, thus providing a signature in the measured wireless channel at the reader, which can be used to isolate sensor signals from other reflections.

The key observation here is that these frequency shift signatures get embedded into doppler shifts in the wireless channel between the sensor and the WiForce reader. Thus, the reader can employ a simple channel estimation procedure to detect these frequency shift signatures by utilizing doppler transforms. However, force sensing does not just require detection of the signal from the sensor. We ultimately need to compute the phase changes across the time at these specific doppler shifts, for which we design a short-time doppler transform that allows reading phase changes accurately to about a degree [6]. To obtain these channel estimates, we can utilize any waveform, which can be used for channel estimates, including FMCW to be compliant with radar sensing or OFDM to be compliant with Wi-Fi protocols.

Thus, by creating these signatures by on-off toggling at the sensor, we enable a highly robust mechanism to wirelessly communicate the force readings via wireless channel variations. Further, this also allows us to generalize to multiple sensors, as each sensor can toggle at a different frequency to create different non-conflicting signatures in the wireless channel, and thus be read simultaneously without interfering with other sensors. In our design, the switching frequency required is in kHz, so the power requirements for the RF switches are minimal and can be met with just a few μW, making it possible to utilize power harvesting methods or a single battery that can last for years without getting discharged.

IMPLEMENTATION AND EVALUATION

We designed the sensor prototype (Fig. 4a) as an 80 mm long and 10 mm wide sensing surface. The sensing surface consists of a flexible mechanical beam, which acts as the length continuum on which forces are applied. This mechanical beam can be made from materials like Ecoflex-30, or be 3D printed with materials like neoprene rubber. Copper tapes affixed to the mechanical beam and the fixed sensor base implement the air-separated microstrip line traces. The height of the air column separating the two traces is kept to 1.5 mm in accordance with HFSS simulations for impedance matching to enable a frequency operating range of 0-3 GHz, with less than 1 dB insertion losses over the entire bandwidth. This makes the sensor compatible with two of the most popular ISM bands in the bandwidth, the 900 MHz frequency band increasingly being used for wireless medical devices and the 2.4 GHz band used by both Bluetooth and Wi-Fi. WiForce reader is implemented on a USRP N210 platform, which performs channel sounding with Wi-Fi compliant OFDM waveforms to read the sensor wirelessly; the sensor can be successfully read even when kept more than >1m away from the reader.

We use a standard load cell mounted below the WiForce sensor to obtain force ground truth and use an actuator to press the sensor at known locations to profile the force localization errors. We test our sensor prototype extensively and observe sub-N errors at both 900 MHz and 2.4 GHz frequencies (Figure 4c), as well as sub-mm localization accuracy (Figure 4d). The performance is slightly better at 2.4 GHz, as higher frequencies show higher phase changes due to smaller wavelengths, and that increases the resolution of phase sensing.

Wireless signals have been known to have difficulty propagating within body tissues due to their high dielectric constants, which leads to exponential losses [10]. Since our technology has important applications in surgical settings, we also perform experiments with tissue phantoms designed to mimic the human tissue composition accurately, to determine the robustness of our sensing paradigm in these challenging propagation settings. We observe no measurable degradation in error performance when testing the sensor over the tissue phantoms as compared to testing the sensor over the air (Figure 4a, b shows the two setups, Figure 4e shows the CDF). This robustness arises due to the capability of the wireless sensing algorithm using doppler shifts, as it can isolate sensor signals even if the sensor signal is heavily attenuated.

We also generalize the sensing strategy to sense multiple sensors simultaneously, by providing each sensor with a different toggling frequency. Also, we test the sensor with human operators applying the forces on the sensor with their fingertips. The sensor was able to both wirelessly localize the finger pressing points of the operators, as well as detect the force levels applied by the finger pressing interaction [6].

CONCLUDING REMARKS

To summarize, WiForce enables a joint sensing-communication paradigm that utilizes the force to phase transduction mechanism created by the soft polymer augmented microstrip line sensor. Our sensor requires only a few μW to both sense and communicate and can be wirelessly read even if the sensor is located centimeters below the body tissues. Thus, WiForce makes headway towards fulfilling the vision of untethered passive force sensors, which are a major requirement for ubiquitous sensing and HCI interfaces, safer surgical instruments, and autonomous robotic surgeries in the future.

WiForce presents one of the first force sensors capable of near-zero power operation. However, our current design has limitations. For instance, WiForce sensing surface is a 1-D continuum that can sense forces only along the length, and can only sense a single force acting across the length. In our future work, we would look into a generalized sensing surface design that can extend to a 2D continuum, as well as the ability to sense and localize multiple forces acting on the sensing surface simultaneously. ■

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REFERENCES

[1] Swadhin Pradhan, and Lili Qiu. 2020. RTSense: Passive RFID based temperature sensing. *Proceedings of the 18th Conference on Embedded Networked Sensor Systems.*

[2] Chengkun Jiang, Junchen Guo, Yuan He, Meng Jin, Shuai Li, and Yunhao Liu.2020. mmVib: micrometer-level vibration measurement with mmwave radar. *Proceedings of the 26th Annual International Conference on Mobile Computing and Networking*, 1-13.

[3] F. Adib, H. Mao, Z. Kabelac, D. Katabi, & R.C. Miller. April 2015. Smart homes that monitor breathing and heart rate. *Proceedings of the 33rd annual ACM Conference on Human Factors in Computing Systems.*

[4] A.L. Trejos, R.V. Patel, and M.D. Naish. Force sensing and its application in minimally invasive surgery and therapy: A survey. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science.*

[5] Jessica Burgner-Kahrs, D. Caleb Rucker, and Howie Choset. 2015. Continuum robots for medical applications: A survey. *IEEE Transactions on Robotics*, 31.6.

[6] A. Gupta, C. Girerd, M. Dunna, Q. Zhang, R. Subbaraman, T. Morimoto, & D. Bharadia. April 2021. WiForce: Wireless Sensing and Localization of Contact Forces on a Space Continuum, *NSDI.*

[7] P. Parzer, F. Perteneder, K. Probst, C. Rendl, J. Leong, S. Schuetz, ... & M. Haller. October 2018. RESi: A highly flexible, pressure-sensitive, imperceptible textile interface based on resistive yarns. *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology.*

[8] H. Lee, K. Park, J. Kim, & K.J. Kuchenbecker. May 2019. Internal array electrodes improve the spatial resolution of soft tactile sensors based on electrical resistance tomography. *International Conference on Robotics and Automation (ICRA).*

[9] Ilya Rosenberg, and Ken Perlin. 2009. The UnMousePad: An interpolating multi-touch force-sensing input pad. *ACM SIGGRAPH 2009 papers*. 1-9.

[10] D. Vasisht, G. Zhang, O. Abari, H.M. Lu, J. Flanz, & D. Katabi. August 2018. In-body backscatter communication and localization. *Proceedings of the 2018 Conference of the ACM Special Interest Group on Data Communication.*