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FERROTAG: WHEN INKABLES MEET WIRELESS SIGNALS

Excerpted from "FerroTag: a paper-based mmWave-scannable tagging infrastructure," from *Proceedings of the 17th Conference on Embedded Networked Sensor Systems* (SenSys '19) with permission. https://dl.acm.org/doi/10.1145/3356250.3360019 ©ACM 2019

Inkjet printed technologies is a type of computer printing that recreates a digital design by propelling droplets of ink onto paper substrates. It is considered a transformative innovation that democratizes the paper-based product fabrication accessible by individual entrants. In recent years, novel functional inks (e.g, nanoparticles-based inks [1]) with consumer inkjet printers enable a more disruptive potential for fabricating low-cost inkable electronics, also known as inkables. Compared with traditional electronics [2], inkables are eco-compatible and easy to use. It is predicted that the market for inkable sensors will reach $4.5 billion by 2030 [3].

In the past decade, the research on inkable sensors and circuits has been driven mainly by materials and engineering communities. For example, an array of new sensory inks provides prints with desired electronic properties, such as conductivity, insulation, hydrophobicity, and hydrophilicity [4, 5]. These inkables can be integrated into diverse sensing applications, such as temperature [6] humidity monitoring [7], chemical analysis [8], and health [9]. Due to the nature of inkable systems, one of the major challenges is how to let inkables interact with other electronic systems for functional integration. Currently, optical interfaces, such as cameras and smartphones [2], are a widely adopted solution due to the fact that most of the inkables have color changing properties.

In this article, we introduce a new inkable design paradigm aiming to integrate functional inkable sensors with pervasive wireless networks. This paradigm will leverage the properties of ferrofluidic inks to modulate and interact with wireless signals. Specifically, along with introducing the novel concept of wireless inkable sensors and illustrating the feasibility, we present *FerroTag* as a new inkable tagging scheme, especially with a focused demonstration to the field of product identification, as shown in Fig. 1. Different from traditional RFID chips [10], FerroTag is extremely low-cost and ecological, and can be fabricated by a consumer printer. Moreover, FerroTag can be read by wireless

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signals in a mass and line-of-sight fashion for the application of product identification, which is superior to the current practice of Barcode and QR code [11].

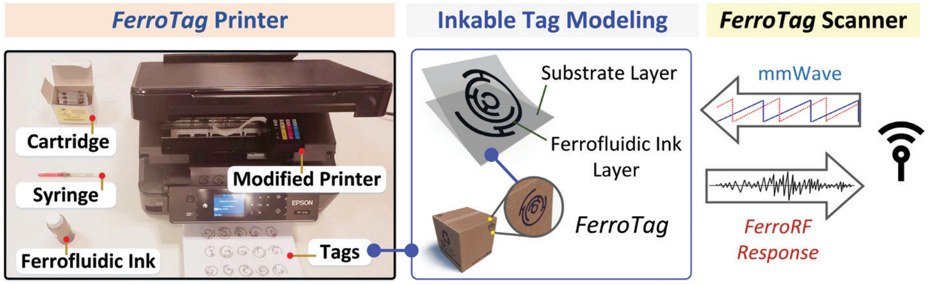

FIGURE 1. FerroTag [12], an example of inkable systems, can be scanned by wireless signals for mass product counting and identification in inventory management.

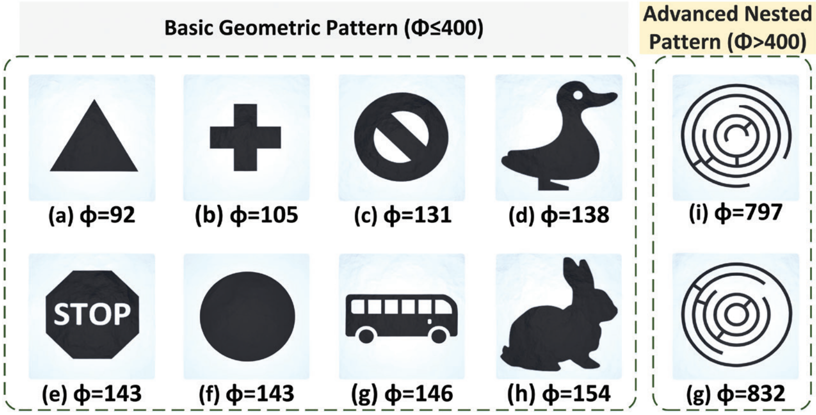

FIGURE 2. Basic geometric and advanced nested tag designs are illustrated with different pattern complexities. The tag capacity is related to the ink pattern design. More complex ink pattern design has the potential to hold more tag IDs. The variance of the histogram is employed to represent the tag pattern complexity as the complexity scores ϕ [14].

FERROTAG AT A GLANCE

The FerroTag mainly contains two parts: (1) Printing a FerroTag through a commodity inkjet printer, (2) Scanning a FerroTag through a wireless signaling device.

Printing a FerroTag

The primary physical components of FerroTag are designated ferrofluidic ink patterns printed on a normal substrate, e.g., paper or plastic substrates. The tag can be manufactured via a variety of easy-to-use, mass-produced, and widely accessible manufacturing methods, including Mass Fabrication [2] and Alternative Fabrication [13]. In Mass Fabrication, a new FerroTag printing machine is designed based on the commodity inkjet printer to rapidly prototype the tags. Whereas, in Alternative Fabrication, FerroTag molds are produced by 3D printing, and then a firm tag can be drawn on the substrate with a basic brush in seconds. In addition, the tag patterns can be highly customized. The tag pattern can be typical geometric shapes, such as triangle, rectangle/square, pentagon, and circle, or more complex forms, as shown in Fig. 2. In addition, to increase the tag capacity and further resist the ink expansion interference, an advanced nested geometric tag pattern is designed, which is a multiple-layer spiral pattern. The tag sizes are also remarkably flexible, ranging from 10 x 10 mm (0.39 x 0.39 in) to 30 x 30 mm (1.18 x 1.18 in).

Scanning a FerroTag

One of the most distinguishing features of FerroTag is that it can be scanned by pervasive wireless signals. In contrast to other electronic interfaces, such as camera and acoustics, wireless signals have an excellent performance in terms of directionality and own the superiority in high tolerance to ambient noises (e.g., sound, light, and temperature), less surface scattering, and higher sensing resolution [15]. In our study, a mmWave probe is proposed to remotely and robustly acquire the tag's recognizable response (hereafter, the FerroRF response) for scanning, as shown in Fig. 3. Specifically, the probe transmits a mmWave signal and processes/demodulates the reflected response signal. Once it receives the data, the tag scanning module first performs the pre-processing to correct the distortion and extracts the spatial-temporal features. After that, an effective classification algorithm is developed to count the tag number and recognize the tag identity. The scanning distance ranges from 0.2m to 10m.

FERRORF EFFECTS, MODELING, SYSTEM

Ferrofluidic Ink

Ferrofluidic ink is a colloidal liquid, in which core components are magnetic nanoparticles (e.g., ferrite Compound-Magnetite powder), a carrier fluid that suspends the nanoparticles (e.g., organic solvent), and the surfactant that coats each magnetic nanoparticle [1]. The quantity and the arrangement of these magnetic nanoparticles reflect into the unique characteristic frequency responses when tags are probed by broadband radiofrequency (RF) signals. When a fundamental tone is passed through the ferrofluidic ink, magnetic nanoparticles modulate the response signal and generate additional frequency tones besides the fundamental one.

Ink-modulated Wireless Effects

In this part, we further explore the ink-modulated wireless effects. When a fundamental tone is passed through the tags, the ferrofluidic pattern modulates the response signal and generates additional frequency tones besides the fundamental one as:

$$r(f,\tau,t) = R_{f,t}(\tau) \otimes h_f(t)$$

where $r(f,\tau,t)$ is the signal modulation function of ferrofluidic due to the stimulation of millimeter waves. $R_{f,t}(\tau)$ is the signal reflection function based on: τ-volume makeup of ferrofluidic, f-range of frequency, and t-time instant. $\otimes$ stands

IN THIS ARTICLE, WE INTRODUCE A NEW INKABLE DESIGN PARADIGM AIMING TO INTEGRATE FUNCTIONAL INKABLE SENSORS WITH PERVASIVE WIRELESS NETWORKS

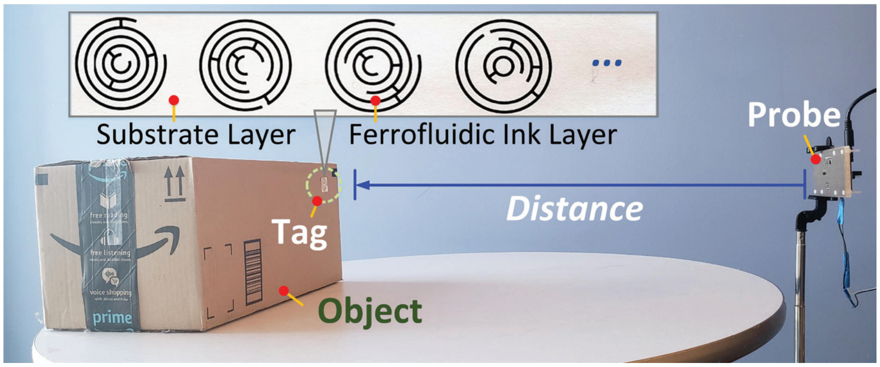

FIGURE 3. The implementation for scanning a FerroTag (designated FerroTags with a mmWave probe).

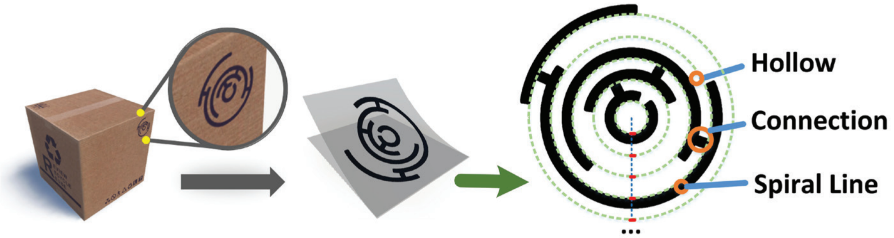

FIGURE 4. The illustration of the tag modeling, including three components: hollow, connection, and spiral line.

for convolution computing, and $h_f(t)$ is the ideal band-pass filter function for the carrier bandwidth.

Tag Modeling and Capacity

To enlarge the tag capacity and strengthen the robustness, the advanced nested geometric tag pattern produces through a series of iterations of components containing three key components: spiral line, hollow, and connection as shown in Fig. 4. These components can be customized by users or randomly distributed as input. For a nested pattern, the number of spiral line layers, the radius of each spiral line, length of each spiral line, and the starting position of each spiral line allow tag capacity to increase exponentially. If we assume that there are five spiral line layers, and six connections, the capacity of the FerroTag can be estimated as

$$(6 \text{ x } (7-2)+2)^2 \text{ x } 2^{2^{5-1}} > 8.5 \text{ x } 10^{12}.$$

Wireless Scanner Design and Implementation

An ordinal FMCW mmWave probe is designed in FerroTag, whose carrier frequency is set up as 24GHz. The bandwidth of the transmitted signal is 450MHz. A pair of four-by-four antenna arrays are designed, offering an antenna directionality of 19.8dBi. The weight of the probe is 45.5g, and the cost for the probe is less than $100. The transmit power of this probe is typically 8dBm with a 5.5V supply voltage under the 1.2W DC power consumption. Besides, the probe can be easily mounted on the wall or integrated with other devices (e.g., police drone, patrol robot, automobile, and smartphone).

FERROTAG TEST IN THE FIELD

We evaluate the ability of FerroTag to recognize the different tags in the controlled lab environment. Two off-the-shelf economic printers (i.e., Epson Expression Home XP-400 and Canon Pixma MG2922) are employed to produce massive tags with 201 different nested patterns. We collect a total of 300 traces for each tag, including 210 traces randomly selected for training and 90 traces for testing. As a result, there are 42,210 traces for training and 18,090 for testing. The resulting average classification performance for each tag is shown on a heat map (aka a confusion matrix) in Fig. 5. The rows represent the selected tag ID classified by the random forest classifier and the columns represent the actual tag ID. The diagonal cells are the darkest blue, implying that the traces were indeed classified correctly. While little light blue cells are appearing outside the diagonal cells, instances of misclassification are rare. The identification accuracy is 99.54%, with 99.52% precision and 99.49% recall, which implies that the feature vector effectively reflects the unique FerroRF response characteristics in each tag.

DISCUSSION AND INSIGHTS

Advantages

To sum up, wireless inkable sensors are featured as: (1) Ultra-low cost: the ink and substrate are very accessible, the cost for each sensor can be less than one cent, much lower than current chip-based sensors (0.18 – 30 US dollars); (2) Environmentally friendly: the sensor doesn't use the conductive ink or the sophisticated toxic specifically designed chemical ink. It is ecological (e.g., organic, disposable, and recyclable material); (3) Battery-free: the tag is entirely passive, requiring no power supply; (4) In-situ: can work in a non-contact (distance up to hundreds meter away), easy to be deployed and maintained, multiple tags are accurately read by a scanner outside the line-of-sight; (5) Flexible: This substrate of this sensor can be the paper or the thin film. And the sensor can be directly printed on the target object surface or manually suppressed to various shapes (e.g., bend, camber, curve, fold, wrap) without permanent deformation, as opposed to other sensors on circuit boards that have to be set in the rigid containers.

Limitation and Challenges

In tag scanning, the classification performance for tag identification is based on the collected ink-modulated response dataset. The sensor performance may degenerate under the complex and unknown working environments. To solve this problem, improvement in the tag scanning part with advanced signal processing and machine learning can help extract the more intrinsic tag response features, which can enable the scanning model generalization and offer new opportunities to make sensors more ubiquitous and adaptable.

Future work

Beyond the use case of the mass objects counting and identification, owing to the concept of the ink-modulated wireless effects and the advantages of ultra-low cost and in-situ, the wireless inkable sensor can replace the barcode, work as a generic solution to extend the interaction area of IoT devices, and serve as the “fingertips” of the next-generation Internet. ■

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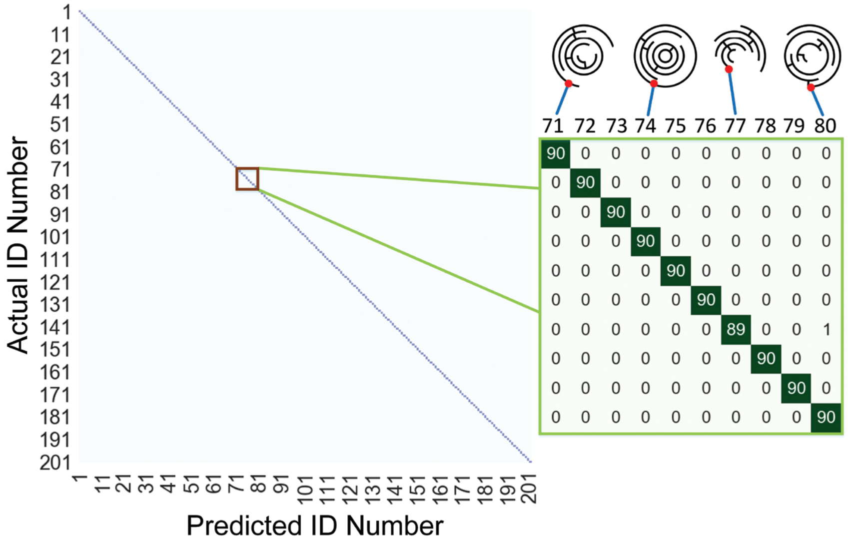

FIGURE 5. The identification performance for FerroTag with 201 different type tags. Confusion matrices of ten types are enlarged in the green box. These ten types are the same as others following the same pattern design. These ten types verify that most are classified correctly.

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