An Implicit and User-Modifiable Urban Sensing Environment

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Abstract

Capturing useful data in a complex and dense urban space is an inherently challenging task. There is so much data people can capture in a city, yet they may fail to capture important information, some of which they don't even know that it exists. In this paper, we discuss an implicit approach to urban sensing and introduce an *implicit sensing system* that combines wearable sensors and mobile phone networks to support early-stage exploration of urban issues. An important technical issue that arose in the development of such sensing system is localization in indoor and urban canyon environments. We discuss the use of RFID tags as easy-to-deploy location reference points that could be installed, modified and reused by end-users. The evolution of *user-modifiable location infrastructure* should reflect and support implicit as well as explicit sensing that takes place in a city.

I. INTRODUCTION

Cities occupy just 2 percent of the Earth's surface, yet their inhabitants already consume 75 percent of the planet's natural resources for goods and services, and 80 percent of global carbon dioxide emission originate in towns and cities [4]. To improve city inhabitants' collective ability to understand the invisible impact of what they do in their everyday life on the global environmental issues, we could exploit personally-owned, location-aware sensors. In particular, GPS-equipped mobile phones together with portable/wearable sensors would allow urban pedestrians to easily capture various kinds of geographically indexed data, which could be voluntarily shared and aggregated to create sensor-powered maps [10] and support *participatory urbanism* [11] as well.

In this paper, we focus on two major limitations of mobile phone-based sensing by pedestrians. First, mobile phones often require users to *explicitly* capture data, which may not be a problem in goal-oriented sensing campaigns [2] that take place *after* environmental concerns arise. However, it is difficult to motivate capture *before* such concerns arise. Second, we need detailed location information to meaningfully interpret and use the sensed data; however, GNSS (Global Navigation Satellite System) technologies such as GPS do not work well in urban canyons as well as indoor and underground spaces.

We developed prototype mechanisms for *implicit* sensing and *user-modifiable* localization infrastructure, which together can alleviate these limitations to empower citizens. *Implicit* sensing is embedded in our everyday activities whose primary goal is not necessarily data collection. Implicit sensing can collect data *before* citizens perceive the need of focused observation. Such data can support early-stage exploration of urban issues.

Participatory Sensing [2] has developed tools and infrastructure for enabling public *campaigns* using networked mobile devices and sensors. Participatory Sensing requires users to *explicitly* register for the campaigns. Opportunistic Sensing [3] is also a system of people-centric urban sensing. In Opportunistic Sensing, users are required explicit procedure for selecting their interest. While the both Participatory Sensing and Opportunistic Sensing require explicit procedure of users, our proposed method is for *implicit* sensing which can extract previously unnoticed and unobservable atmosphere. Nokia's Sensor Planet [1] also proposed a platform for collecting and sharing sensor data for human centric sensing. However, for urban sensing, we need to consider about how to analyze and extract the meaningful information. EQUATOR e-science project [8] mapped carbon dioxide levels using mobile sensors. Our proposed system considered to extract environmental information by sensing human body as well as directly sensing the environment.

We first examine the data from a preliminary indoor experiment using pressure-aware slippers [15]. This informs the iterative design process of the WINFO+ system [5][12], which allows city-wide *implicit* sensing in the wild. Our preliminary experiments with WINFO+ suggest that such footwear-based sensing can reveal interesting information provided that there is a pervasive location infrastructure that 'seamlessly' covers a city. This leads to the discussions on user-modifiable, decentralized localization infrastructure for urban sensing, which can be developed by extending and integrating our RFID-based localization system [14]. We believe that WINFO+ together with the *user-modifiabl*e localization infrastructure allows people to collect meaningful data in a city.

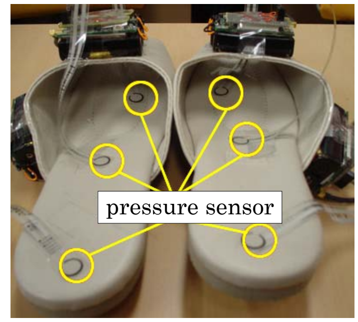


Fig. 1: Sensor-enabled slippers.

II. Implicit Sensing: The Case of Sensor-Enabled Footwear

To better understand the challenges and implications of implicit sensing, we have embedded networked sensors in footwear. We began by analyzing the data from pressure sensor-enabled slippers [15] focusing on pressure distribution and its correlation with a person's walking patterns. The prototype integrates normal slippers, Crossbow MICAz Motes, and three pressure sensors to wirelessly send pressure data to a server. The server then performs relevant signal processing. The three pressure sensors are embedded at the front, the center, and the back on the surface of the slippers (see Fig.1). We asked our subjects to walk with this prototype, and identified distinct signal patterns for the normal, shuffle, and forward-bending walking.

We call the period during which a pedestrian's foot contacts the ground an *epoch*. By extracting peak values from the front and rear sensors within an *epoch*, we can closely examine what goes on within each *epoch* and classify *epochs* into the following four groups:

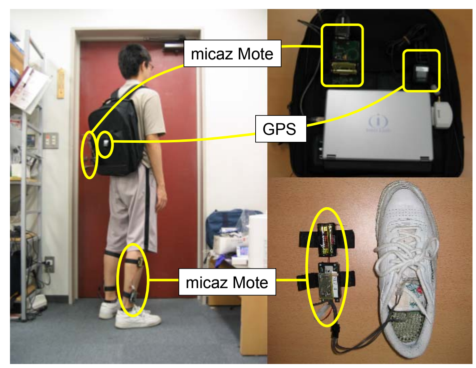


Fig. 2: Prototype of WINFO+ Client.

Group A: Peak values from the front and rear sensors are high. This suggests smooth movement in normal walking.
Group B: Peak values from the front and rear sensors are low and high, respectively. This suggests shuffle walking.
Group C: Peak values from the front and rear sensors are high and low, respectively. This suggests forward-bending walking.
Group D: Peak values from the front and rear sensors are low.

Overall, our basic data analysis suggests that small inexpensive sensors, if integrated in footwear, can capture what mobile phone-based sensors cannot easily capture. Interestingly, footwear devices can capture data without requiring a user to *explicitly* perform data capture operations. However, footwear-based *implicit* sensing is different from surveillance as the sensing is carried out through the users' personal devices and they must be able to fully control the process of (not) capturing, storing, and disclosing data.

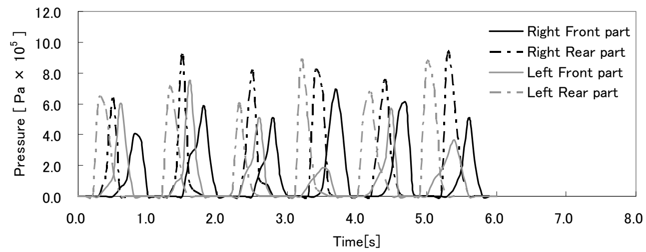
The idea of integrating shoes and sensors [9] is not new. However, a city-wide urban sensing requires a durable and easy-to-use device, scalable and adaptive system architecture, and reliable positioning infrastructure that works both indoors and outdoors. Based on the basic analysis, we developed a footwear sensing system called WINFO+ [5]. It is based on a client-server model and composed of WINFO+ Client (WIC) and WINFO+ Server (WIS).

A WIC is a wearable device that consists of a personal computer, "probe shoes," a GPS receiver, and wireless interface (see Fig. 2). The personal computer wirelessly obtains the pressure data from the shoes. The data are tagged with the GPS timestamp and compressed by using the four epoch types. WICs then transmit the data to a

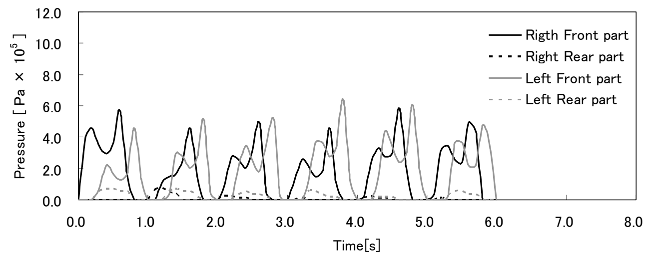
WIS, along with the latitude, longitude, epoch type, and timestamp information. In our prototype, WICs can communicate with a WIS virtually anywhere in a city by using the PHS (Personal Handy-phone System) technology.

WINFO+ is designed for *adaptive sensing* in diverse device, information and resource environments. WICs should acquire the right amount of information depending on their screen size and CPU power (*device adaptive* sensing). Also, WINFO+ should respond to dynamic behavior of data (*information adaptive* sensing). For example, we might need finer-grained data when the data change substantially either in temporal or spatial axes. Moreover, the system should be able to determine the frequency of sensing and transmission depending on the amount of battery power left (*resource adaptive* sensing).

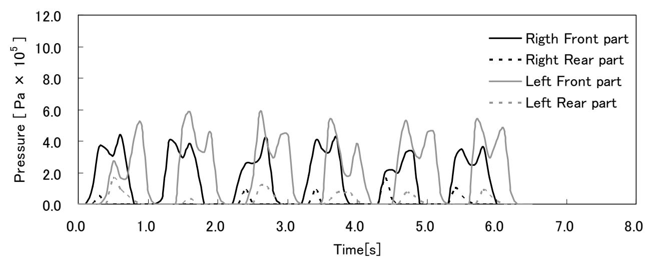
The WIC prototype is easy to wear and designed to look socially acceptable in most public spaces. Using the prototype, we carried out small-scale experiments in real urban spaces. Three male graduate students wore the prototype and walked in a Central Tokyo area near Akihabara without drastically changing walking styles: they walked spontaneously along a street, crossed the street by using a pedestrian bridge, and stopped at a train station. Figs. 3 and 4 show sample data from one of the subjects. This experiment showed that footwear-based city-wide sensing can reveal characteristics of the surfaces on which pedestrians walk as well as wearers' walking habits. We also acknowledged the importance of location information in interpreting and using these sensed data.



(a) Flat areas.



(b) Stairs (upward).



(c) Stairs (downward).

Fig. 3: Temporal change in pressure.

III. USER-MODIFIABLE LOCALIZATION INFRASTRUCTURE

GNSS technologies such as GPS do not work well in urban canyons, indoor/underground spaces, and so on. This can be problematic when people want to collect location-relevant sensor data in such spaces. As demonstrated in the following scenario, RFID tags can be used as location reference points for urban sensing, thereby complementing GNSS technologies:

> *Imagine an apartment complex that may have an air contamination problem. The residents can install RFID tags at their front doors to help citizen scientists collect air quality data in the building. Mobile sensor devices can obtain unique IDs from the tags, and then retrieve corresponding 3D location information by querying a database. The tags could also be used for implicit sensing. For example, mailmen's shoes capture and accumulate location-indexed pressure and temperature data in the building over a year, which may be later found useful to discuss remodeling of the building for elderly people.*

An important issue here is the motivation and the deployment cost to physically install the tags, measure their positions, and update the database. WiFi-based localization [7] require little deployment cost only when WiFi stations are already deployed in the environment. In contrast, RFID-based localization uses inexpensive RFID tags that can be easily deployed on demand at a wide variety of places.

In Japan, the government has shown keen interest in RFID location reference points [14] and already embedded about a hundred "intelligent benchmarks," which are equipped with passive RFID tags, in the city of Kobe. We surely need much more RFID reference points to fully cover a city-wide area: perhaps, millions of them (e.g., at 10-meter intervals).

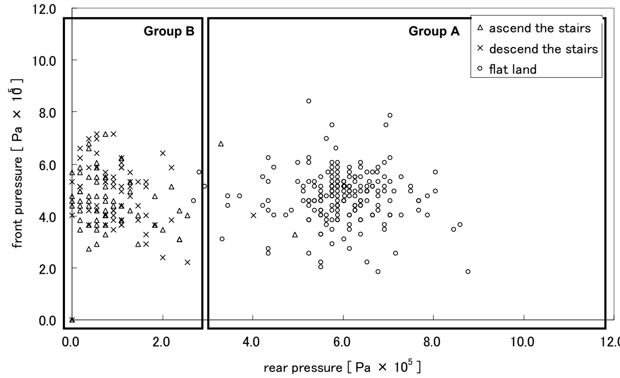


Fig. 4: Front-rear diagram.

Although government-initiated centralized deployment can be heavyweight and costly, they can hire professional land surveyors who have the skills to install high quality reference points in terms of physical robustness and information accuracy. An alternative approach is the citizen-initiated decentralized deployment that is more scalable in terms of the number of tags. We envision a hybrid, *user-modifiable* environment in which a small number of strategically allocated quality-assured tags (T1) and a large number of end-user tags (T2) coexist. In such a user-modifiable environment, we can reduce the overall deployment cost by reducing (1) the number of tags that must be installed and (2) the cost to install each tag.

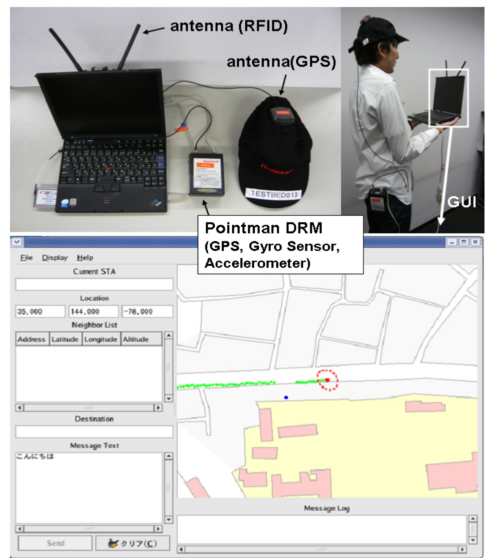


Fig. 5: P2P-based localization system.

As shown in Fig. 5, we have developed a P2P-based localization system that reduces the number of required tags. The pedestrian device can estimate its position using GPS, (active) RFID location reference points, dead reckoning modules (Honeywell GyroDRM™), and location information shared by colocated pedestrians. Research [6] shows that the combination of RFID, GPS, and dead reckoning can improve positioning accuracy in both indoor and outdoor environments even without such location information sharing. Our system uses GPS if the satellite signals are available. Otherwise, the system operates without GPS by obtaining location information from a nearby RFID tag. Even when the user's device is away from RFID tags, it can estimate the position by using dead reckoning modules. However, as pedestrians move and time passes by, the positioning error increases. In our positioning mechanism, colocated devices exchange their location estimation (along with relevant error estimation) with each other in order to cooperatively reduce the positioning error considering human mobility patterns. We carried out an experiment in a *54m x 63m* space on a university campus and verified the effectiveness of the cooperative location estimation.

To reduce the cost for installing each tag, we have developed a mechanism that automatically estimates the position of a newly installed tag by collecting location information from pedestrians who pass by the new tag [13]. This mechanism allows people to simply put a tag without manually updating the database. We developed a prototype and tested it on a university campus, and found that the location estimation error of a new tag quickly decreases and stays below *2 meters*.

These mechanisms together can support the ecology of location reference points by facilitating end-user deployment. As our scenario may suggest, existing environmental concerns could motivate end-users to install location reference points. However, implicit urban sensing without clear value proposition may not directly motivate end-user installation. We would like to understand end-user installation from an ecological perspective rather than a narrow scope of cost-benefit balance. For example, people may be able to reuse location reference points that were installed for some other purpose. Such practices cannot be prescribed, but could be facilitated by technological and social systems.

IV. Discussion and Conclusion

The combination of WINFO+ and the user-modifiable localization infrastructure enables implicit city-wide sensing that can reveal characteristics of ground surfaces as well as walking habits. Note that mobile phone clocks can provide a means to tag sensed data with timestamps when GPS is not available. Our approach complements mobile phone-based *explicit* sensing and allows people to capture some data *before* environmental concerns arise. Similar approaches could be used for other kinds of wearable sensors (e.g., heart rate, temperature, moisture, and blood pressure sensors).

Allowing for participatory contribution of both sensor data and location reference points can create exciting opportunities; however, it can also introduce issues around data quality, security, and privacy. How should we deal with variability of data quality, and "junk reference points" that could degrade the localization accuracy? Implicit sensing unobtrusively collects data from users' body areas as well as spaces inhabited by people. Capturing and sharing such data could cause serious privacy problems. We are currently exploring different approaches to address these issues.

WINFO+ exploits mobile phone communication (Personal Handy-phone System) for disseminating sensor data. Advances in mobile phone technologies may allow tighter and flexible integration of wearable sensing devices and mobile phones in the future. In addition, an increasing number of phones are integrated with RFID, Bluetooth, and 2D barcode technologies. We can design location reference points that exploit these technologies so as to complement GPS and facilitate location-indexed data collection by mobile phones.

Finally, it is important to acknowledge that supporting participatory urban sensing is more than just creating easy-to-capture, easy-to-share, and easy-to-modify environments. People need to have information and skills in order to meaningfully participate in collaborative sensing and sensemaking. This motivates a future work to design an integrated support environment for urban data practices.

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