Investigation of the waste-removal chain through pervasive computing
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Environmental sustainability and energy management are increasingly critical issues in people’s lives and their livelihood. New and rapidly evolving tracking technologies are major tools for addressing these challenges because they provide visibility to the otherwise hidden processes of everyday infrastructures such as those involving waste removal. By revealing these processes and patterns, the technologies can help influence personal behavior with respect to environmental consciousness. Pervasive monitoring and analysis can also improve environmental sustainability by revealing inefficiencies in the waste-removal chain to municipalities and waste service providers, as well as monitoring compliance with environmental regulations. We present a tracking system for trash that demonstrates how pervasive monitoring can help to better reveal, understand, and improve the waste-management system. Custom-developed Massachusetts Institute of Technology (MIT) “trash tags” use the Global System for Mobile communication technology to provide both coarse localization and active return communications. We discuss methods for calculating and visualizing movement of trash and present preliminary results from the Trash Track project, including information about tag performance and discussion of some acquired traces. With the Trash Track project, the MIT SENSEable City Laboratory is exploring how new pervasive sensor technologies can be used to transform and understand cities.

Introduction

In the last two decades of the twentieth century, the gross domestic production of industrialized countries rose by 60%, whereas their population grew by only 10% [1]. This has led to a rise in waste generation per capita, increased production of hazardous waste, and growing concern about the environment. For example, in the United States, 254 million tons of municipal solid waste was generated in 2007, which is nearly triple the amount from 50 years earlier [2]. The increasing complexity of the removal chain poses system challenges for effective disposal and treatment of products that have reached the end of their useful life. In addition, governmental interventions and environmental directives are placing pressure on suppliers to proactively assume responsibility for the recovery of their manufactured goods, by establishing a closed-loop supply chain that captures and properly treats these “end-of-life” products. An effective closed-loop supply chain requires an efficient monitoring system for tracking end-of-life products through refurbishing, remanufacturing, and recycling facilities.

The evolution of pervasive computing since its origin in the mid-1970s has led to extensive application of sensors that influence the technological tools used in people’s daily lives. Progress in developing “smart dust” — that is, small autonomous sensing, computing, and communication systems that form integrated distributed sensor networks [3] — provides an opportunity to investigate large-scale complex slowly evolving systems. The rates of technological progress in sensing, computing, and data processing are starkly higher than the evolution of other systems such as the waste-management systems in urban cities. More specifically, new and rapidly evolving pervasive technologies such as tracking sensors can generate localized information about the movement of waste in the removal chain, providing insight about disposal and appropriate recovery of waste.
The extensive literature with regard to pervasive computing and its impact on urban infrastructure can provide guidance for tracking trash. The waste system is challenging to profile because of the unpredictable paths that trash can follow. Pervasive computing can enable an unconstrained and detailed view of the city and its flows of people and goods [4], as well as the flow of end-of-life products. Previous applications of pervasive computing to unconstrained urban systems include applications that involve traffic systems, wastewater flow, and energy management. Roozemond discusses the application of pervasive computing in producing autonomous intelligent agents as observed in urban real-time traffic signal-control systems [5]. Schutze et al. discuss the impact of computing technology in optimizing the control strategies for urban wastewater system [6]. Tompros et al. propose a solution for making use of pervasive network architectures to benefit energy management services for the residential sector and power distribution network operators [7].

Other projects have specifically focused on the application of pervasive sensing to trash, albeit in restricted fashions. In particular, radio frequency identification (RFID) technology has frequently been proposed as a solution for identifying trash products during end-of-life processing. Thomas explores the application of RFID technology for improving waste management by labeling the goods to be recycled [8]. Binder et al. suggest using RFID tags for the automatic separation of recyclable materials [9]. On the other hand, other scholars such as Wager et al. argue that the material composition of RFID tags will contaminate the quality of recyclable materials [10]. While RFID technology has several advantages, as discussed in a later section, RFID tags are not able to transmit data over long distances. This severely limits their utility in unconstrained systems, and thus, many projects with a global scale have made use of different technologies.

In a project conducted by Greenpeace that involves following the trail of electronic waste (e-waste), the organization employed Global Positioning System (GPS) tracking devices and attached them to broken television sets. The project uncovered illicit practices of U.K. recycling companies that resold the defunct appliances as second-hand goods to developing countries, thus violating European Union regulations [11]. Other projects involve less technologically advanced, more labor-intensive tracking approaches. Ebbesmeyer et al. have been following thousands of drifting objects on the Pacific Ocean, including 29,000 rubber ducks that fell from a container ship in 1992. Based on the observed positions, the researchers formulated models of oceanic currents [12]. While taking advantage of escaped objects to track ocean currents has a low environmental impact, releasing sensors into the environment may have adverse consequences. Koehler and Som question the impact of ubiquitous computing on the environment [13].

In this paper, we address the application of pervasive computing to the waste-removal system. We present a tracking system for monitoring and analyzing the waste-removal chain that is based on the attachment of “trash tags” (combined GPS/Global System for Mobile communication [GSM] location sensors) to waste objects, and we discuss preliminary findings. The tags are designed to rely on a widely deployed existing global infrastructure—the GSM for cellular technology—which provides both coarse localization and an active return communications channel. We discuss the hardware and software structures of the developed location tags. We also discuss the calculation of the movement of waste through the waste-management system of a city, both in real time and retrospectively. Preliminary results of the Trash Track project are presented.

The goal of this paper is to show how pervasive tagging and computing can help us better observe, understand, and improve waste-management processes. Revealing the motion of waste through the removal chain is an effective method for investigating the end-of-life destinations of aggregated waste. This unique perspective of waste-management networks can be used to increase public awareness of environmentally harmful consumption and waste-disposal practices. Furthermore, this bottom-up view of the removal chain will assist municipalities and service operators in improving the logistics of removal processes. The Trash Track project demonstrates the considerable potential for better understanding and improving the removal chain through applications of pervasive computing.

**Research methods**

The methodological decisions discussed in this section are divided into two different areas: 1) the design of the location sensors and 2) the organization and implementation of the deployment process.

**Technological development**

Development and implementation of tracking systems is complicated by wide variation in application requirements and in the capability of available technologies. Application requirements vary in many dimensions, including precision, power consumption, signaling requirements, infrastructure availability, cost, and form factor. The requirements of the trash-tracking application primarily involve low cost, long life, and active geolocation reporting, assuming that the environment and path of the tag cannot be controlled or confidently predicted once deployed.

When evaluating the environmental impacts across different waste streams, the choice of an appropriate tracking methodology is important. There are a variety of technological choices for real-time location sensing such as RFID, outdoors General Packet Radio Service, the GPS, the GSM, and other communication alternatives such as Wireless Fidelity (Wi-Fi)** (wireless local-area network
Passive RFID tags are an attractive solution that is already commonly used to track items in retail supply chains; the low price of these tags makes them cost effective to deploy in large quantities. However, in the trash-tracking scenario, the path of the tags cannot be predicted a priori, which makes it difficult to know where to deploy the required RFID reader infrastructure. While an RFID solution could conceivably identify which trash reached a set of predetermined locations, it would not be able to track the most interesting cases of trash, those that went astray from expected paths. Information privacy and security is also a major concern to officials when the deployment of RFID is discussed [14].

Although GPS is an attractive choice because of its precision and the steadily declining cost of GPS chipsets, the use of GPS tracking systems may lead to discontinuity in signal transmissions, since it is difficult to guarantee that tags will be in locations that can receive GPS signals. Augmented GPS based on pseudolite transmitters (i.e., high-power nonspace-based GPS transmitters called pseudosatellites, or pseudolites) might address some of these problems, but the infrastructure required for this is generally unavailable in rural areas.

There are other low-cost communication infrastructures with varying breadths of deployment. Urban areas typically have extensive wireless coverage from multiple technologies, including Wi-Fi and WiMAX; a variety of cellular technologies are prevalent in the United States, including code-division multiple access, GSM, and Universal Mobile Telecommunications System. Of these, the most globally ubiquitous infrastructure is GSM cellular technology. Because GSM technology is mature, the cost of GSM chipsets has been also steadily declining.

Active reporting infrastructure is critical to tracking object movement in an unconstrained system such as the waste-removal chain. The biggest advantage of GSM location technology is that it provides a solution for location sensing and, at the same time, a communications backchannel. GSM provides a coarse-grained localization capability based on the set of reachable cell sites and an active return communications channel through those cell sites. The primary disadvantages of GSM are its high cost relative to RFID and the low positioning accuracy relative to GPS or Wi-Fi cell positioning; however, the requirements for global reach and unsupervised deployment exclude those alternatives.

### Design process

The tracking system for monitoring and analyzing the waste-removal chain is based on active location-reporting tags attached to individual waste items. These trash tags were developed at the Massachusetts Institute of Technology (MIT) by utilizing an off-the-shelf GSM data modem chipset, microcontroller, motion sensor, and a custom printed circuit board (PCB) with an integrated trace antenna. After gaining deployment experience with the first-generation tags, a new design was developed prior to the second production run; this design reduced the size and cost of the device. It also incorporated several designs for manufacturing improvements by reducing the part count, making the transition to the Telit** GE864 GSM modem from the Telit GE862 GSM modem, and transferring the PCB antenna onto the main board. The second generation of the tag is 30 mm × 70 mm × 15 mm in size and has two months of lifetime under average use conditions. Figure 1 illustrates the design of tags developed with GSM technology, and Figure 2 illustrates the system flowchart for the tags. In Figure 2, the term filtering refers to per-tag trace filtering, which is the process described later in this paper that involves Gaussian distributions.

The development process was focused on simplifying tag design to 1) reduce power requirements to reduce battery size; 2) shrink the form factor using a low-cost small antenna design; 3) make use of fewer electronics; and 4) minimize packaging without sacrificing the robustness needed to survive impacts in the removal chain.

To minimize power consumption, the tag is equipped with an algorithm that utilizes an exponential back-off timer that awakens the tag upon detection of motion by the motion sensor. The tag uses the cell survey mode of the modem to scan all channels and bands for cell towers; it locates the strongest 12-cell sites nearby and stores their identification information. Subsequently, it compresses tower reports into Short Message Service (SMS) messages and periodically sends them back to a server via an SMS gateway. Each text message contains one or more survey results, including the local time when the message was sent, the time that the survey was taken, and whether the tag was awoken by the motion sensor.

After power consumption was successfully minimized, a second design goal was to keep production costs low. Generally, production volume and form factor have the most critical effect on cost. The form factor is mainly dependent on the antenna, the battery, and the component integration (influenced by unit volume). A third effective trait of the tag is its passive use of signals for localization. The tags are programmed to communicate with low data rates (< 100 Kb/s over the lifetime of the unit) such that, with high deployment, cost-effective rates can be achieved. Moreover, the tags are capable of effectively transmitting signals over the global range of GSM infrastructure designs.

A challenge with the current localization methodology is that tags often finally arrive in rural areas with a few alternative cell tower destinations to choose from. A potential solution would be to increase the rate of signal transmission when motion is detected to make best use of signal reception while available. This may improve tracking...
The tags, which cost about $60 each in quantities of 1,000, are designed and manufactured with the goal of making them as environmentally benign as possible, beyond compliance with international environmental standards. The second generation of tags was modified to use components containing very little or negligible hazardous substances, and the assembly process was designed to produce a lead-free final product. In addition, the tags were designed to minimize resources used in production and minimize waste load and production energy. As a result, the GSM tags are compliant with environmental standards such as the European Union Restriction of Hazardous Substances Directive (RoHS), which is designed to monitor and reduce the consumption and disposal of hazardous substances that are commonly used in the manufacture of electronic equipment.

**Deployment process**

**Deployment logistics**

This paper focuses on the first two deployments in which we deployed 303 GSM tracking devices attached to waste items provided by volunteers in Seattle, Washington, and 15 GSM tracking devices in New York, New York. The deployment initiative was designed to actively involve local citizens in the deployment process, particularly in providing waste items from various categories. Volunteers were recruited through an open call in local media asking them to sign up online to receive further instructions about the deployment protocols. Each volunteer was asked to provide 15–20 items from a comprehensive list of waste items. SENSEable City Laboratory researchers directly tagged or supervised tagging of trash items, either in volunteer homes or in public institutions. Once the tagged trash was disposed of, the transmitted data was collected at a central server, which stored traces and mapped the waste path through the removal chain.

As might be expected, most volunteers who signed up for the experiment had a strong interest in environmental issues and technology. When asked for their reasons for participating, most expressed curiosity and a lack of information about the waste-management process.

**Preparation of tags**

The process of tagging waste with the sensors required several steps to achieve proper signal transmission while protecting the tags from damage. The tags were shrink-wrapped twice to avoid contact with liquid. Half of the tags were immersed in a 1- to 2-in-thick shock-absorbing layer of sturdy insulation foam based on epoxy resin.
The remaining tags were protected using a latex mold rubber. The tagging process was found to be a very delicate task given that a few main objectives had to be met: protection of tags from physical damage, proper signal transmission, and concealing the presence of tags to prevent manual removal.

**Selection of municipal solid waste**

Waste items for Trash Track deployments were carefully chosen by considering the following: 1) a wide range of waste, which is categorized into municipal solid waste definitions by the U.S. Environmental Protection Agency; 2) environmental impacts of each waste category (including such considerations as hazardous elements in e-waste, the energy that can be saved by remanufacturing tires, and material recovery potential of appliances); 3) waste production levels and significance; and 4) alternative routes for removal of waste (e.g., recycling, remanufacturing, reuse, and landfilling). The waste items were carefully chosen to represent the diverse origins of municipal waste from residential, commercial, and industrial sources. As a result, 49 product types were organized into 15 waste categories, with higher priority for tagging given to the specific group of products listed in Table 1.

**Data acquisition**

The GSM sensors send an SMS text with the identification information of the 12 closest cell phone towers in the vicinity. We then determine the location of each observed cell tower by querying an online triangulation service provided by Navizon, Inc. We note that access to the mobile triangulation application programming interface (API) of Navizon was provided free of charge for the duration of the experiment. In many cases, different cell ID numbers report similar physical coordinates. Therefore, to avoid overweighting those points, the duplicate coordinates from the computation are discarded, and the algorithm retains only one of the colocated sites.
For each survey point, the distribution of site locations is recorded. Moreover, the minimum intersite distance is computed and used as the scale for a Gaussian probability distribution centered at each observed site. This logic ensures that the probability distributions centered at each site location become more diffuse as the overall distribution of locations becomes more diffuse, ensuring that the tightest cluster of points registers as the most heavily weighted cluster in each new survey point.

This probability distribution is also localized in time from the observation of the survey through the time of the next survey. After a site is no longer observed, the weight of its probability density function (pdf) is reduced by a weight based on a logistic function “s-curve” with 50% decay after 15 minutes. These pdf’s are then superimposed in space and time. This results in the most general representation of the location of tags, as it captures the relative likelihoods of different locations. This methodology can be particularly useful for observing correlated motion of multiple sensors such as tags that travel in the same vehicle.

The pdf is used to identify a single location that represents the maximum-likelihood position for each point in time. The programmers search for the space by testing only the points at actual observed cell locations to determine the highest likelihood among those points. Then, the weighted average of all points within a 1-km radius of that maximum is computed; this is considered the most likely estimate at that point in time. The maximum-likelihood points are utilized for display and visualization purposes.

**Table 1** Trash items tagged in the experiment, organized by category. (CRT: cathode ray tube; LCD: liquid crystal display; MP3: MPEG-1 Audio Layer 3, where MPEG stands for Moving Picture Experts Group.)

<table>
<thead>
<tr>
<th>Category</th>
<th>Items</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Paper</strong></td>
<td>Corrugated carton boxes, Newspapers, Folding and milk cartons</td>
</tr>
<tr>
<td><strong>Plastic</strong></td>
<td>Polyethylene (PET) bottles: e.g., water or other beverage bottles, High-density polyethylene (HDPE) bottles: e.g., milk, detergent, and shampoo bottles</td>
</tr>
<tr>
<td><strong>White goods</strong></td>
<td>Refrigerators, Room air conditioners, Washing machines, Clothes dryers, Dish washers</td>
</tr>
<tr>
<td><strong>Metals</strong></td>
<td>Aluminum cans, Steel cans</td>
</tr>
<tr>
<td><strong>Other organics</strong></td>
<td>Tires</td>
</tr>
<tr>
<td><strong>E-waste</strong></td>
<td>CRT monitor, LCD monitor, printer cartridges, Cellular phones, Portable digital audio players, Computer, desktop and laptops</td>
</tr>
<tr>
<td><strong>Hazardous waste</strong></td>
<td>Lithium rechargeable batteries, Fluorescent bulbs, Alkaline rechargeable batteries</td>
</tr>
<tr>
<td><strong>Composite bulky waste</strong></td>
<td>Furniture</td>
</tr>
<tr>
<td><strong>Glass</strong></td>
<td>Beer and soft-drink bottles, Food, other bottles and jars, Incandescent bulbs</td>
</tr>
</tbody>
</table>

**Preliminary results**
While a larger analysis of the acquired data is still underway, we discuss preliminary results of the experiment through a technical analysis of the sensor performance and a discussion of some of the traces acquired through the experiment.

**Performance of the tags**
Because of the varied nature of the conditions experienced by individual tags, it is difficult to clearly define the expected lifetime. Because the sleep mode is a very low-power mode relative to when the cellular module is active, the lifetime is significantly affected by the amount of time that the tag is actually in motion and by the algorithm for turning on the system in response to vibration.

**Figure 3** gives some insight into battery consumption for a sample of tags deployed in a controlled test. In this test, in cases of continuous motion, the module would sleep for at...
least 5 minutes after taking a measurement, and that sleep
duration would be linearly increased up to 1 hour. The same
figure shows the distribution of “active time” over the
lifetime of ten sample tags. The data was collected by
reporting the total uptime and total active time in each
message. These numbers can then be plotted to show the
evolution of the “burn rate” (i.e., battery dissipation rate)
over time. Each curve in the figure represents the
performance history of an individual tag, comparing the
number of hours the cellular module of a tag has been active
with the number of hours that the tag has been running.
The slope of the curve represents the effective duty cycle
over that time period. Note that the scales on the axes are in
a ratio 1 : 40, meaning that a 45°-line would represent an
effective duty cycle of 1 : 40. The timing of the reports is not
uniform because the reporting intervals are determined by
when the tag reports data.

The deployment proceeded in three phases, which can be
observed in the plot. In the first 100 hours, the tags were active
but were being prepared for deployment. Since they were
being handled by the deployment staff, motion was observed
to varying degrees for different tags. After being prepared,
the tags were mailed to several volunteers who would
apply them to pieces of trash. This is observable in the
steep segment in the 24–48 hours following the preparation
phase. Because the tags were moving quickly, observations
of new cell sites would trigger the back-off timers to reset
frequently, with the result that the tags were active nearly
continuously. Once they reached the volunteers, the tags were
applied to trash items and disposed of. In this phase, different
pieces of trash fared differently until the end of the traces.
The data is characterized by brief periods of activity in which
the burn rate is high and long lulls during which the tag is
primarily asleep. The burn rate in this period varies between
1 : 20 and 1 : 40.

In some instances, the tags experienced very long lags.
For example, tag 987 was deployed to a volunteer in a remote
part of Scotland, whose trash was only collected once per
month. Since the tag arrived too late for the monthly
collection, it lay dormant for 600 hours before reactivating.
Nearly vertical lines indicate periods of significant
motion.

The traces did not end at a uniform time, either because
the tags were destroyed or their batteries expired. We estimate
that this version of the tags had sufficient energy to operate
between 20 and 30 hours in active mode and between three
and six months in sleep mode. Because the tags consumed
approximately 50% of their available energy during
shipment, the tags in this particular experiment had a
reduced lifetime.

Lifetime can also be extended by tuning (i.e., adjusting)
the algorithm to minimize wasted energy when in motion.
The trash-tracking application is unusual among tracking
applications, in that the tags may be destroyed at their
destination. It is critical to get the “last message” out before
they are destroyed; however, it is also critical to avoid
unnecessary operation when in motion for long times.
Thus, simply decreasing the duty cycle may lead to much
worse application performance.

Acquired traces
Using the setup described earlier, we were able to acquire
a set of traces for the two cities of New York and Seattle.
As illustrated in Figures (4a) and (4b), the location
reports we received have a low resolution, due to the
power-conserving measures explained earlier. However,
the resolution is sufficiently high for inferences about the
route and the mode of transportation. As an example,
Figure (4a) shows a traversal path for a printer cartridge,
and Figure (4b) provides the trace associated with the
removal of a Panasonic videocassette recorder from
a disposal site in Seattle, Washington, to a landfill
located in north Oregon along the Interstate highways
90 and 82.

Given the harsh environment in the waste-disposal system,
electromechanical failure of tags was a major challenge.
Tags failed for any number of reasons: They could be
destroyed during the waste-removal process before sending
a location report, or they could arrive in an environment
where the transmission signal was blocked. Other possible
reasons include hardware malfunctions of the tracking
device or human errors resulting from volunteers not
disposing of the tagged item. We found that the failure rates
heavily depended on the packaging strategy. Among the
described packaging methods, the rubber packaging gave
the lowest failure rates—46% for rubber versus 72% for
foam packaging. However, rubber packaging also involved
the most time-consuming method. Overall, we observed
that electronic waste items were less prone to failure than
regular household trash, which is understandable given the
more severe physical forces involved in regular garbage
collection. For most of the traces, battery failure was
determined to be less of a problem compared to physical
destruction.

Investigating the valid traces, it quickly became obvious
that electronic waste and hazardous waste tend to travel
the longest distances. Furthermore, the acquired traces reflect
the structure of the removal system in general; from tags
dispersed throughout the city, we eventually received a
large number of reports from a large recycling facility in
Seattle.

Conclusion
Population growth, accelerating waste generation, and
growing concerns about the environment have made the
removal chain increasingly critical. End-of-life procedures
have evolved into complex distributive networks involving
growing numbers of municipalities and service operators
(e.g., collectors, transfer stations, and recycling centers), waste categories (e.g., e-waste and paper), and end-of-life mechanisms (e.g., recycle, landfill, remanufacture, and refurbish). This is creating challenges for municipal waste managers and service operators to effectively supervise the movement and proper treatment of waste in the removal process. Figure 4

Traversing paths. (a) Printer cartridge in the removal chain traveling south. (b) Trace of an e-waste item, following the interstate system southeast.
chain. More specifically, increasing complexities in communication networks among stakeholders make it difficult for municipalities and service operators to evaluate the end-of-life destinations of aggregate waste. Pervasive computing is opening a new frontier for studying urban environmental systems such as waste management.

In this paper, we have addressed the application of pervasive computing to the waste-removal system. We have presented a tracking system for monitoring and analyzing the waste-removal chain by attaching real-time location-sensing tags to the waste, utilizing GSM cellular technology for coarse localization and active return communications. We have discussed the hardware and software structures of the tracking sensors and the methodologies for computing the movement of waste through the removal chain.

The data acquired from the deployment of GSM tracking sensors in Seattle and New York also provided insights with regard to shortcomings of the Trash Track system. Trash tags could fail because of physical damage in the removal chain, enclosure in an environment where transmission signal was blocked, improper tagging, and device malfunctions. The type of waste object also had an influence on the ability of a tag to report; for example, sensors attached to or embedded within electronic waste had higher chances of success than household items.

Preliminary results of the Trash Track project reveal the motion of waste through municipalities and multiple service providers along the removal chain. Analysis of each trace provides a complete narrative of the journey of that item through the waste-management process, including the disposal location, final destination, transportation distance and time, number of transfers, and other useful information. Comparing the observed waste-removal process with the expected case can help service providers understand how well the system performs and whether it can be improved to be more energy efficient or ecologically responsible. Additionally, making these traces viewable will enhance public environmental awareness about the removal chain and promote responsible consumption and disposal practices.

Future directions for the Trash Track project will further investigate the impact of pervasive computing on the removal chain. More specifically, the Trash Track researchers will map out all the acquired traces and determine the links (i.e., transfer stations and recycling facilities) that waste passes through in the waste-management networks. This will enable a comparison between the monitored end-of-life processes and the optimal end-of-life treatments for waste. Regarding product development, the Trash Track project will continue improving the GSM tags while investigating tag designs that can provide higher accuracy, smaller size, and better cost effectiveness.

This paper builds on previous work at the MIT SENSEable City Laboratory in its exploration of how the increasing deployment of sensors and mobile technologies radically transforms how we understand and describe cities. The understanding of the cities, their real and virtual processes, and the behavior of their citizens opens many opportunities for intervention and feedback to produce change.

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