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Tracking Trash

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Abstract—Using active self reporting tags we were able to follow the journey of 2,000 objects through the waste management system of Seattle. We used this data to define measures of efficiency for what could be called the ‘removal chain’. We found that over 95% of the traces reached a compliant end destination. However, there were concerns with special categories of waste (cellphones, e-waste, and household hazardous waste) and specific geographic locations (trash from Bellevue and Redmond in particular did not follow the recommended best practices). We believe that similar studies may increase knowledge and systemic performance of waste management systems and, at a personal level, reduce the ‘out of sight out of mind’ attitude to trash.

I. INTRODUCTION

Pervasive computing technologies are becoming an integral part of contemporary life and an invaluable tool for research scholars all over the world [1] [2]. Increasingly, we are witnessing real-world deployments of technologies such as sensor networks, GPS tracking devices and RFID in such diverse domains as transportation [3], tourism [4], urban living [5] [6], and entertainment [7]. However, apart from a seminal study by Lee and Thomas [8], not much work has yet focused on waste management. In contrast to [8], our work presents a more comprehensive study with results based on a large number of sensor deployments at the urban scale. Our paper aims to leverage the great advances in pervasive technologies that have been recorded over the past few years to fill in this gap.

Trash is one of today’s most pressing environmental issues, both directly and as a reflection of our attitudes and behaviors. A central concern in solid waste management is the lack of quality data on all the processes involved. This consequently affects the detailed assessment of the environmental impacts of waste collection, processing and disposal, the efficiency of waste logistics, and ultimately, the impact of waste transportation on the benefits of recycling. Under current regulation, states, cities and companies are required to report information related to waste generation, collection, and disposal. However, these aggregate numbers often do not reflect the fine grain processes involved in waste management.

We introduce a project called *Trash Track*, which paves the way for more extensive usage of pervasive computing in the environmental context. We designed a special self reporting tag to follow 2,000 waste items during

their journeys through the waste stream. By making the waste ‘removal chain’ more transparent, we seek to reveal the disposal process of everyday objects, and highlight potential inefficiencies in the current removal system. We believe that similar studies using pervasive technologies can create awareness and promote behavioral change, reducing the ‘out of sight out of mind’ attitude to trash.

We also believe that the project helps policymakers and service providers to be better informed about the functionality of waste removal systems. And in order to inform policymaking and waste systems design/management more efficiently, this kind of experiment needs to be done periodically and at a larger scale.

II. METHODOLOGY

The aim of Trash Track is to study the removal system in a new way using pervasive technologies, and in turn raise awareness of how waste impacts the environment. For the first time, it unveiled the life after death of everyday objects – the journey of trash.

A. Trash Track

Trash Track project is being undertaken by the SENSEable City Lab at Massachusetts Institute of Technology and is inspired by the NYC Green Initiative [9]. The project focuses on how pervasive technologies can expose the challenges of waste management and sustainability. The goal is to understand the “removal-chain” as we do the “supply-chain,” and how we can use this knowledge to build more efficient and sustainable infrastructures.

Thousands of small, smart, location-aware tags were employed during this project; the first step towards the deployment of smart dust – networks of addressable, locatable, and small micro-electromechanical systems [1]. These tags were attached to many different trash items, which were then monitored as they traveled through the city’s waste management system. Figure 1 shows a schematic diagram of the experimental setup. The sensors were localized by the means of cell tower ID triangulation. We used sensors that augmented the cell tower ID triangulation with GPS for further refinement of the localization. Trash Track builds upon previous research undertaken by the SENSEable City Lab ([10] [11] [6]

[12] [13]), which focused on how the increasing deployment of sensors and mobile technologies may radically transform the way in which we understand and describe cities.

B. Data Acquisition

To follow the journey of the disposed objects in the removal chain, we required tracking devices and a suitable deployment method. Here we describe our approach to tracking trash and assimilating data for analysis.

1) *Tracking Device:* Using existing technologies, the locations of trash items were measured and reported periodically. Our first generation of trash tag (see Fig. 2(a)) was based on GSM cellular phone technology and estimated the tag position using the Cell-ID triangulation technique – it measured signal strength from each cell phone tower in sight of the device and compared it to the geographical positions of the towers. Although the accuracy was not as good as GPS, it tended to be more robust. Cellular signals can be picked up inside buildings and from within piles of trash – not requiring an unobstructed sky view. The sensor’s specs are:

- OSRAM SFH 7710 orientation sensor
- PIC18LF2620 microcontroller
- 128 KB serial port EEPROM
- Quad-band PCB antenna
- Telit GE864 GSM M2M modem
- GSM sim card
- 900mAh Lithium Polymer battery

Our second generation of tracking tag used the best of both worlds – GPS and CDMA cell-tower trilateration. Based on the Qualcomm inGeo™ platform (shown in Fig. 2(c)) in combination with Sprint’s cellular network, this current version of the tag used the Qualcomm’s gpsOne® technology to provide both accuracy and availability. We plan for our future generations of tag to work seamlessly across CDMA/GSM/UMTS networks, which will consequently allow them to be tracked across international borders. The second-version tag’s specs are:

- Qualcomm MSM6125 chipset
- M36W0R6050 (8 MB NOR + 4MB PSRAM)
- Motion Detection using a passive vibration sensor
- GPS
- CDMA 2000 (800 MHz and 1900 MHz)
- 720mAh Lithium Ion battery

Along with the nGeo®’s Low Duty Cycle (LDC) technology, we developed a “duty cycling” algorithm that ensured a long enough lifetime¹ to track the trash to its final destination. This also provided hibernation capability that kept the tag off most of the time, with its position sensed and reported every few hours. An accelerometer was used to keep the tag in hibernation mode if no movement was detected, further extending the battery life.

¹The lifetime of the device depended on external factors such as amount of movement of the object and cell network coverage. We observed a lifetime of three to six months on a six-hour reporting cycle per device.

When movement was detected, it woke up the tag to check and report its new position. The sampling rate was varied in response to conditions sensed by the tag. Specifically, a set of orientation sensors were used to monitor changes in location, which increased the location sampling rate when the tag was apparently moving or when previously unseen cell tower IDs were observed.

All of the components used in the tags were RoHS (Restriction of Hazardous Substances Directive) compliant. The toxic material levels for the tags were below both U.S. and European Union standards for electronic products, which allowed for the Trash Track tags to be legally introduced into the waste streams.

2) *Trash Tag Deployment:* Trash Tag Deployment: Deploying tracking devices to follow trash, made a trivial task like throwing away trash a complex operation. Inserting the Trash Track tags into the waste removal chain required attention to a number of critical aspects:

- Types of waste used – an assortment of objects were chosen to be tagged and disposed of, reflecting characteristics such as component materials, type of technology, object size, and product functionality.
- Practicalities of tagging – the approach taken to attaching the tags to the objects and how to protect them.
- Collection of metadata – each tag’s disposal origin, ID number, specifications, and type of waste was recorded.
- Disposal process – different locations and modes of disposal were used.

The tag deployment took place in Seattle over the course of six months in October 2009. A large part of the tagged waste objects were deployed by the SENSEable City Lab researchers with additional help from several volunteers in the Seattle area and its surrounding regions. The volunteers were recruited through an open call in the local media and were asked to sign up via the project website. 90 households and six schools participated in the experiment during which they were visited by our research team who attached the active tags to the trash items after checking their suitability for tracking and recording additional metadata. The volunteers were then asked to dispose of the tagged items in their normal manner. A sample trash item and tag is shown in Fig. 2(d). In order to protect the sensor from potential physical damage, the tag was waterproofed and covered with a 1-inch thick shock-absorbing layer of sturdy insulation foam (shown in Fig. 2(b)). Clearly, this process was not appropriate for all types of trash. Consequently items that were smaller than the tracking device were excluded in order to preserve their original shapes. Since the tracking device contained lithium batteries and was classified as hazardous waste, the organic trash items were also excluded from tagging in order to prevent potential contamination of composting sites.

In addition to the data of reported locations from the deployed tracking devices, information about the material properties and photos of tracked waste items, along with

Figure 1. System overview.

(a) First generation of trash tags

(b) Tag protector (foam and rubber-based on GSM cellular technology ber)

(c) Second generation of tags uses GPS and CDMA cell-tower triangulation based on Qualcomm's gpsOne®

(d) A sample trash tag

Figure 2. Trash tag.

Figure 3. A sample of trash traces – reported locations of 27 disposed cell phones.

their time and location of disposal were recorded. All survey and real-time tracking data were compiled into our database. At the end of December 2009, all sensors stopped reporting their locations and the dataset was consolidated. Before the data could be used for our analysis, a cleaning process was performed which removed faulty reports such as location artifacts due to poor cellular network coverage.

From the 1,977 tags deployed, we were able to receive at least two location reports from 1,915. Out of these reports 1,279 traces were longer than 250 m. The short traces were most likely the result of either a blocked transmission signal or the destruction of the sensor during

the course of the waste collection process. We therefore excluded these short traces from our analysis. Further data cleaning was done visually examining traces to extract those that did not enter the waste removal system – either they did not leave the participants' homes or the sensors were removed manually. As a result, we retained 1,152 traces for our analysis. An example of the traces of 27 disposed cell phones is depicted in Fig. 3 where some reached as far as a wireless phone recycling facility in Florida.

III. ANALYSIS AND RESULTS

The data collected by the Trash Track project allowed us to study different aspects of the removal chain. In this current study, we were particularly interested in the origins and destinations of trash, as well as the efficiency of the waste management system – where does trash go? Does trash end up where it was destined for?

A. Category of Trash

Eleven trash categories were created by grouping together types of trash that were expected to exhibit similar behavior based on their disposal mechanism, material

content, and likely end-of-life fate. A list of the categories and a brief description follows.

- 1) **Cell phones:** exclusively cellular phones.
- 2) **E-waste:** included computer equipment such as CRTs, peripherals, and accessories, and other household electronics.
- 3) **Glass:** included only single material glass items, such as bottles, jars, and glass tableware.
- 4) **Household hazardous waste (HHW):** included both universal waste items, such as fluorescent bulbs and certain types of rechargeable batteries, and other waste items not suggested for regular household disposal e.g. spray cans and some household cleaners.
- 5) **Metals:** included aluminum and steel cans and small scrap metal pieces.
- 6) **Mixed:** included all types of materials that were suggested for regular household waste disposal, either because there was no other recycling or collection mechanism, or because the product mixes several materials that were not separable using current strategies.
- 7) **Paper:** included plain paper, card, cardboard, corrugated cardboard, periodicals, books and other plain paper products.
- 8) **Plastic Bottles:** included HDPE and PET plastic products, the majority of which were bottles.
- 9) **Other plastic:** included polypropylene, polystyrene, PVC, and other non-PET, non-HDPE plastic products.
- 10) **Plastic-coated paper:** included milk cartons, coated paper cups, Tetra Paks, and other coated paper products.
- 11) **Textiles:** included clothing and textile home goods.

B. Origins

According to the physical addresses noted from the interviews, which were validated with the reported locations from the tags, we divided disposal locations into 12 areas. The disposal locations were most concentrated in the central part of Seattle which was consistent with it being at the center of our tag deployment operation, but they also showed a more diffuse cover of the surrounding areas such as Redmond, Bellevue, and Issaquah. The geographic locations of these trash origins are shown in Fig. 4, with the total number from each area summarized in Table I.

C. Destinations

After being disposed of trash items were handled by the waste management system where (based on reported locations) the majority ended up in Seattle and nearby areas. However, some other items traveled further across the U.S., reaching an assortment of destinations in states such as California, Florida, Georgia, Idaho, Ohio, Tennessee, and Texas. All 1,152 tagged trash items reached 110 different destinations (detail is given in [14]). Geographic

Figure 4. Disposal locations.

TABLE I.
DISPOSAL AREA AND CORRESPONDING NUMBER OF TRASH ITEMS
ALONG WITH LABELS DEPICTED IN FIG. 4

Disposal area	Amount of trash items	Labels (Fig. 4)
Seattle (Central)	420	Seattle
Seattle (North)	109	N
Seattle (South)	74	S
Seattle (East)	101	E
Seattle (West)	27	W
Seattle (North East)	135	NE
Seattle (North West)	46	NW
Seattle (South East)	11	SE
Seattle (South West)	45	SW
Redmond	15	Redmond
Bellevue	10	Bellevue
Issaquah	37	Issaquah

locations of these final destinations are shown in Fig. 5 and Fig. 6 (zoomed-in version in Seattle area) where their IDs correspond to the locations given in Table ??.

The tracked trash items arrived at a multitude of facilities. Understanding the type of end-of-life treatment being performed at each facility was important for characterizing the behavior of the waste system. Based on the type of these end locations, we classified 110 into five groups: Landfill, Recycling, Special, Transfer, and Transit.

- 1) **Landfill:** represented permanent waste disposal facilities intended for household waste.
- 2) **Recycling:** included facilities intended to handle household recycling.
- 3) **Special:** included all facilities intended to collect or process wastes outside of the municipal treatment system, such as drop off centers, manufacturer-owned treatment facilities, and specialty recyclers that focused on specific products.
- 4) **Transfer:** included facilities intended to collect and temporarily store household waste and recycling before it moved on to landfill, recycling, or special treatment centers.
- 5) **Transit:** included those identified as being on a common freight transit route or at a shipping center such as an airport or a port.

Figure 5. Locations of final destinations in Seattle and corresponding ID numbers (see Table ??).

Figure 6. Locations of final destinations in Seattle area and ID numbers (see Table ??).

Note that the end locations were based on a map matching, which was done in a semi-automatic way. For a first approximation, the location reports were automatically compared with a database of waste processing, transporting, and storage facilities maintained by the US Environmental Protection Agency (EPA) [15]. In a second step, these results were cleaned by manually verifying each location with the help of online maps and business directories.

Knowledge of the wastes final destination allowed for an interesting examination, based upon the different categories of trash and their end-of-life locations. The distribution of trash items stratified by their category is presented in Fig. 7 as an absolute value and a percentage in the upper and lower plots respectively. Plastic-other and Paper were the largest categories with over 200 items each, while Cellphone was the smallest with only 27 items. Furthermore it was found that the majority of Glass, Metals, Paper and Plastic items ended up at Recycling facilities. A large portion of HHW and E-waste items reached Special facilities, whereas Textiles, Mixed, and Cell-phone tended to be more random in their types of destination.

Figure 7. Destination types of different trash categories. While the majority of Glass, Metals, Paper and Plastic items reached Recycling facilities and a large portion of HHW and E-waste items ended up at Special facilities, Textiles, Mixed, and Cell-phone appeared to be more random in their destination types.

Similarly, Fig. 8 shows both the actual counts and percentages of the different types of destinations stratified by the waste's area of disposal. The majority of trash items from each point of origin reached recycling facilities. It was noted that a large portion from South East Seattle ended in landfills in stark contrast to the Redmond area, which saw none of its waste terminate in a landfill. Meanwhile South Seattle and Bellevue led the way in their employment of special facilities, both observed the greatest portion of waste headed to special facilities. Overall, most waste objects reached recycling facilities while the second largest portion ended up in landfills and transit facilities.

D. Efficiency of Removal Chain

The general goal here was to understand and evaluate the existing waste removal system. We simply wanted to find out if trash goes where it's supposed to go. It turned out that evaluating the removal system based on the appropriateness of the end-of-life facilities was not so trivial. Different points of view revealed different results. In this study, we viewed its appropriateness from two different perspectives – one from the *best practices* recommended by the City of Seattle and the other from the *contracts* made between the City of Seattle and waste management companies.

1) *Best Practices*: The reported fate of each trash item was categorized as *best practices*, *acceptable practices*, or *not meeting acceptable practices* based on the trash type of each item. The City of Seattle publishes a best practices guide for municipal waste and recycling, both as a flier

Figure 8. Destination types of different disposal areas. Most waste items reached recycling facilities while the second largest portion ended up in landfills and transit facilities.

circulated to the community and as an interactive guide online [16]. This guide was used to determine the best practices disposal procedure for each trash item as recommended by the City of Seattle. The destination of each trash item was characterized as meeting or not meeting the best practice set forth, based on the information about the destination facility. The acceptable practices were also determined based on information about the destination facility. The type of the trash item was compared to the list of materials and products accepted for treatment by the facility to determine acceptable practices. This facility specific information was determined by facility type and description, publicly available facility information, and in some cases by contact with these facilities. A trash item that arrived at a facility where it was not listed as acceptable for treatment at that facility was designated as not meeting acceptable practices. Figures 9 and 10 show the results of the best practices in disposal procedure for each trash category and disposal area, respectively – where ‘Good’ implies best practices, ‘Fair’ means acceptable practices, and ‘Bad’ refers to neither best nor acceptable practices.

It turned out that while other categories of trash appeared to follow the best practices closely, Cell phones, E-waste, and HHW categories raised some concerns about not meeting the best practices guideline with a relatively large portion falling into the ‘Bad’ practices category. A large portion of trash items from Bellevue and Redmond also seemed to not follow the recommended best practices. Yet, overall, from the perspective of the best practices as recommended by the City of Seattle, the removal chain appeared quite efficient with over 95% of trash reaching appropriate facilities.

2) *Contracts*: The City of Seattle had contracts with waste collection companies such as CleanScapes Inc., Cedar Grove Composting Inc., and Waste Management

Figure 9. Evaluation of different trash categories by best practices. While other trash categories appeared to follow the best practices closely, Cell phones, E-waste, and HHW categories raised some concerns about not meeting the best practices guideline.

of Washington, Inc., for garbage collection services [17]. The collection contracts covered different areas and types of waste. Essentially, for a given disposal area and disposed item type (e.g. waste, recycling, composting, special disposal), the end-of-life facility could be identified according to the contracts. With our collected data, we validated if trash items had reached their intended destinations. It turned out that only a small portion of disposed objects reached the facilities specified in the contracts. Fig. 11 and 12 depict the portions of tracked trash items that arrived at the facilities specified in the contracts and different types of destinations reached by them elsewhere – based on the categories of trash and disposal areas respectively. Trash items from Issaquah and Redmond appeared to reach contracts’ destinations more than other areas. Validating the efficiency of the removal chain from the perspective of the contracts for waste collection, leads us to conclude that if those contracts were meant to send trash to the most appropriate facilities, then trash did not traverse well in the removal system with less than 10% reaching the correct facilities.

IV. LIMITATIONS OF THE STUDY

The relatively small sample size of our trash traces (1,152 items) was the first limitation of this study. Nevertheless, we tried to diversify the trash categories and disposal areas to represent the actual waste stream as much as possible. Moreover, the validation of our trash traces was done in the laboratory rather than in the field. This meant that we did not physically identify the tracked trash items at their terminal locations. The last reported positions served only as indicators of the end-of-life locations. In addition, because of the differences in waste

Figure 10. Evaluation of different disposal area by best practices. A large portion of trash items from Bellevue and Redmond appeared to not follow the recommended best practices. Overall, the removal chain appeared quite efficient with over 95% of trash reaching appropriate facilities.

management practices across the US and the relatively small sample size, the results are difficult to generalize. However, the study points to significant gaps in the way how waste management practice is currently being monitored: while existing data collection mechanisms determine quantities processed at individual facilities, the flows of different waste streams between companies, facilities, and across administrative boundaries are not represented in traditional data collection. Our study points to the complexities and distances involved in the processing of electronic and household hazardous waste – and illustrates the urgency for more data collection especially for these waste streams.

V. CONCLUDING REMARKS

Trash is an issue that reflects both our attitudes and behaviors. Through the use of pervasive technologies, the Trash Track project not only seeks to raise awareness of the impact of waste on our environment, but also highlight the potential inefficiencies present within today's removal system. Nearly 2,000 tracking devices were deployed in and around the City of Seattle to monitor the journey of trash through the current waste removal system. The types of objects disposed of and the locations of disposal were carefully selected, to ensure a broad array of disposal locations and waste types were represented. Furthermore, data collected at our server allowed us to explore the efficiency of the removal chain in more detail. Based on the best practices disposal procedure recommended by the City of Seattle, over 95% of disposed objects reached compliant waste facilities. On the other hand, a much

Figure 11. Evaluation of different trash category by contracts. Less than 10% of trash items reached the correct facilities.

Figure 12. Evaluation of different disposal area by contracts. Trash did not traverse well in the removal system with less than 10% reaching the correct facilities.

lower portion reached facilities that were specified in the contracts made between the City of Seattle and the waste collection companies. The results also suggested that more emphasis should be placed on Household Hazardous Waste (HHW) in terms of better informing people about its disposal. Moreover, the list of waste facilities identified in the contracts needs revisiting or updating, in order to ensure the appropriate removal chains are in place – particularly in Seattle and Bellevue.

Besides the analysis of origins and destinations, which is the focus of this paper, we also found that based on the reported stops and velocities, it was possible to estimate means of transport. We observed that recyclable materials (mostly paper and plastic, also e-waste) were very likely shipped out of Seattle's harbor with locations reported from Vancouver, Canada and other stops en route

to the Pacific Ocean. Much of Seattle's waste bound for Columbia Ridge Landfill reported from railways, which was consistent with the method specified in Seattle's waste hauling contracts [17]. Electronic and Household Hazardous Waste (HHW), was often observed to be transported by air, which can be attributed to the take-back collection using courier services.

For researchers who wish to track a large number of items in a similar way, we learned from our experiment that the research design needed to also consider many potential sources of error that were introduced due to the physical conditions in the waste stream. In the beginning of the experiment, only about 20% of the tags kept reporting after entering the waste stream. By the end of the experiment, we were able to raise the success rate to about 80% through the following measures: (1) special protection of the tags against liquid and physical shocks by enclosure with sturdy epoxy foam; (2) placement of tags with special consideration of signal pathways, i.e. preventing signal blockage through metal parts of the tagged objects; (3) concealment of tags within the tagged object to prevent identification and removal by recycling personnel; (4) adjustment of reporting intervals in order to maximize battery life. Given the typical pace of waste removal, we had good experiences with reporting intervals of three to six hours; (5) prior research into removal mechanisms and collection methods and destinations will improve the experiment and can be obtained by reviewing municipal contract documents.

We believe that the project opens the door for policy-makers and service providers to be informed by detailed information about the functionality of waste removal systems. As technologies such as the one developed in this project mature and decrease in cost, such deployments could be done periodically and at a larger scale, to provide sound informational basis for policies to be built upon and to enable troubleshooting of the waste removal system in real-time.

We hope that the project will promote behavioral change and encourage people to make more sustainable decisions about what they consume and how it affects the world around them. Furthermore, we hope that this project encourages the uptake of pervasive computing in the environmental context.

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