Lessons Learned Using Ubiquitous Sensors for Data Collection in Real Homes

Jennifer Beaudin, Stephen Intille, Emmanuel Munguia Tapia
Massachusetts Institute of Technology
One Cambridge Center, 4FL
Cambridge, MA 02142 USA
{jbeaudin, intille, emunguia}@mit.edu

ABSTRACT
Interface design for the home requires a realistic understanding of the complexity and richness of the human activities that go on there; it is our goal to develop tools that enable HCI investigation in actual home environments. We have developed a kit of ubiquitous sensing devices and over the past year have conducted a series of studies installing a large number of sensors, of diverse types, in multiple homes of participants not affiliated with the research team. As we deployed our portable kit outside the laboratory, we encountered unanticipated study design and technology requirements that will affect the continued development of the kit itself. We offer practical tips we have learned from our experience and describe how we are applying them to the design of our next generation of sensors.

Categories & Subject Descriptors: H5.m. [**Information interfaces and presentation (e.g., HCI)**]: Miscellaneous.

General Terms: Design, Experimentation, Human Factors.

Keywords: Home recording, sensors, data collection, research methods, ubiquitous, ethnography.

INTRODUCTION
There is a growing commitment to developing technologies that integrate into the home and personal activities, as evidenced by lab-based research (e.g. [6, 5]) and ethnographic efforts (e.g. [4, 7]). Our group has been focusing on deploying large number of sensors, of diverse types, in multiple homes of participants not affiliated with the research team [5]. While testing strategies for installing and using our portable kit in homes, we have developed a rich understanding of the challenges and opportunities of conducting this kind of research.

Right now, our experiences are guiding the development of our next generation portable kit and are suggesting topics of research we would like to pursue, including privacy and behavior intervention design. In this paper, we offer some practical tips for research teams wishing to use sensing technologies to collect data about human activities and hope that our "lessons learned" offer insight about how to overcome the challenges inherent in ubiquitous data collection in actual home environments.

CHI 2004, April 24–29, 2004, Vienna, Austria.
ACM 1-58113-703-6/04/0004.

DEPLOYING A PORTABLE INVESTIGATION KIT
The core element of our portable kit is a set of simple, inexpensive sensors that can be affixed to objects with physically manipulated open-close or on-off states, such as doors, light switches, appliances, cabinetry, and containers. Each sensor consists of three components: a thin wire reed switch, a magnet, and a storage board with coin battery, encased in a small plastic pillbox. These sensors record timestamps in response to actions inhabitants take on the environment, such as opening the fridge.

Other elements of our portable kit include infrared beacons that can be placed on the ceiling and detected by a wearable receiver attached to a lightweight backpack for crude user position-tracking [3]; wearable accelerometers strapped on the arm or leg to record limb position and movement [2]; video, microphones, and stationary or wearable time-lapse cameras for high-bandwidth data collection; and experience sampling on a handheld computer (PDA) to query the user about activities and personal states [5].

Studies Using the Portable Kit
We have conducted two studies in the homes of members of the research team and three studies in the homes of paid participants, including a woman in her 30s, a woman in her 80s, and a family of four. These investigations range in length from one weekend to ten weeks, with the typical installation in a participant home being two weeks. All investigations included use of a large number (40-100) of open-close sensors and are often supplemented with the variety of other sensing tools in the portable kit.

These first studies have focused on collecting labeled datasets to train activity recognition algorithms [8], but we have also examined applications of the data to inform the design of interior spaces, to encourage inhabitants to be reflective of their behaviors, and to begin identifying opportunities for information presentation [1].

Procedure

For each of our participant studies, we provide informed consent forms approved by our institute review board. These forms comprehensively describe the technologies of the portable kit, the type of data that will be collected, procedures for storing and reporting results without compromising confidentiality, and the participants' rights with respect to leaving the study and/or requesting the removal of data.

We spend 3-5 hours installing the sensors and other components of the portable kit, working in teams of about five people. Video and audio require positioning of devices and software set-up on laptops storing the data. Participants are given a demonstration of how to put on the accelerometers, position-tracking, and/or wearable time-lapse camera and instructed in the daily recharging of batteries for these devices.

The infrared beacons for position-tracking are easily affixed to the ceiling using small amounts of putty. The main challenge with this aspect of the installation is deciding where to place the limited number of beacons, each having a narrow (approximately) 2 foot diameter range. We tend to focus placement on doorway arches, in connecting spaces such as stairs or halls, and above major seating areas where few open-close sensors are regularly activated, such as couches in the living room.

The open-close sensors can be placed on a variety of objects, and are typically concentrated in the kitchen, with its cabinetry, appliances, and even portable containers ("the cookie jar") and the bathroom, where water-splashed faucets, wicker hampers, and personally-sensitive areas such as the toilet and medicine cabinet present special challenges. We also place these sensors on bureau drawers, light switches, closet doors, and entry and room doors.

Following installation, the kit is left in place, unsupervised for the duration of the study period. The sensors are then collected and the data uploaded, synchronized, and analyzed. Participants are interviewed about the experience and may be asked to talk through their common home routines and label sections of data.

LESSONS AND CHALLENGES

We are in the early stages of deploying the portable kit, but each installation is informative. The following include both practical tips and more broad design concepts that we have gleaned from our experiences over the past year.

1. The sensors must remain in position throughout the installation period, but a major concern is preventing damage to the host objects. Participants' homes contain a variety of delicate surfaces, from cherished antique wood to easily affected cabinetry finishes and finding non-damaging adhesives has not been a trivial issue. We've had the most success with electrical tape as an adhesive agent; it is less likely to mar finish or paint on removal, but can still hold on high-use objects and protect the sensor boards from water damage. However, humidity or poor attachment can cause the tape to fail. For instance, we have found it necessary to return a few days after many installations to re-secure about a quarter of the sensors that have fallen due to moisture, attachment, people, or pets causing failure. We advise researchers to **anticipate object and environment conditions** that will affect installation, including moisture, quality of surface finishes, typical movement of the object, and inhabitants' methods of interaction with the object.

2. Our current installation requires us to secure the open-close sensors at three points of contact: the sensor box, reed switch, and magnet. We try to place the larger sensor box on an interior shelf or in a position out of the way so it is not brushed against. The magnet and switch, however, need to line-up on open-close events, and a significant portion of the installation time, which averages between 3-15 minutes per sensor, is spent insuring that the open-close is consistently recorded. We recommend **reducing points of contact for sensors** that will be affixed to working surfaces in the home to speed installation, minimize opportunity of damage to the host object, limit opportunities for dislodgement, and make the sensors less noticeable.

3. After the removal of sensors for one study, the participant exclaimed that finally the apartment "looked clean" again, highlighting the effect that sensor visibility has on the study experience. We have also noticed that event-triggered LEDs on the sensors constantly remind the inhabitants of being observed, potentially affecting their behavior. We recommend that the **visibility of sensors be minimized**, by keeping the form factor small, matching sensor casing to surface colors, positioning sensors out of view, and eliminating event-triggered LEDs.

4. We have found our participants to be poor at estimating the probability of use of objects. They will assert that something will not be used anytime soon during an installation period, only to be proved wrong when something unexpected occurs, such as a light burning out or a pet getting sick. We therefore recommend that **sensors be placed wherever possible** without regard to estimated use frequency.

5. The researchers might also inadvertently constrain what behaviors are captured, for example in deciding on position-tracking beacon locations. As the goal is to capture a rich record of behaviors, especially those that would be unexpected in a traditional design process, and to make installation fast, installers should not have to spend significant time reasoning about correct sensor placement. **Redundancy, made possible by having many sensors, is one approach to minimizing assumptions and reducing installation time**.

6. Our original design approach was to make the coding and technology as simple as possible, and this seemed to be by avoiding the broadcasting and receiver coordination required of real-time data collection. Instead, the current sensors are synchronized before installation, and events are

time-stamped and stored on the sensor. The other portable kit elements are similarly deployed, with final synching of the multiple data streams occurring after the study. Considerable preparation and post-study time is required, and we have encountered problems with elements that are affected by clock drift, such as the video and audio, which can vary as a function of the machine serving the device. We have had to use highly visible or audible events such as the refrigerator opening or the lights turning on, to aid us in synching a video stream to the record of events from the open-close sensors. As a result of these frustrations experienced with each study, we have decided that **the extra development work required to make tools "real-time" and wireless, stored and time-stamped centrally, is worthwhile.**

7. Data collected from homes is most useful if activity labels are associated with the corresponding sequence of sensor activations. The most labor-intensive approach to generating these labels is direct observation. The more typical approach of diary logs is vulnerable to recall errors. Instead, we employ experience sampling on a handheld computer [2] to query the participant throughout the installation period for labeling of their current activity. As we have reported, even this in-context approach is sensitive to the mental models and motivation of participants and does not always provide sufficient detail for multi-tasked, distributed, rapidly-occurring, and category-bending activities that define a big portion of our daily lives. Given the importance of labeling and the challenges that existing methods present, we propose that **labeling interfaces be designed to identify moments when participants are receptive to the task and in a position to adequately describe their activities**. An interface that is event-triggered or that recognizes the participant's task transitions or idle moments, may be an appropriate solution.

8. Open-close actions on the environment provide a compelling record of daily routines, with seemingly nebulous activities like getting ready for work or making a meal describable by a series of discrete events. However, we have also found that much of what is done in a day, such as watching TV, resting, reading, and "working" is not adequately captured through our initial sensing approaches. Participants report that they improvise and use objects that are out in the open (a mug in the drying rack), so some elements of a routine frequently go unrecorded. The older participant deliberately kept objects outside of drawers, closets, and cabinets, to compensate for sensory and motor impairments. The family of four came to recognize that when they were most productive, they moved less, combined activities, and triggered fewer events. These findings all suggest that the interpretation of sensor activations, for applications such as health monitoring or ubiquitous interfaces, can't be one-dimensional, but must **take into consideration individual differences and the improvisational, efficient nature of behavior**.

9. **Participants need to feel that the research team is respectful of their homes and their time.** We ask participants to be present during the installation, so they can monitor how we interact with their personal space. To avoid overwhelming the participant, we have learned to break down the installation into two days: one to introduce the technologies, go over the informed consent forms, and get a tour of the home and one to do the actual installation. We also sequence where we work to complete high-use rooms first, such as the bathroom, and to avoid "being everywhere at once," so participants have a room to retire to during the hours we are there.

10. Participants expressed that they were pleased to be contributing to our research, but they still indicated some notable moments of discomfort that suggest **issues of privacy are more subtle and complex than generally recognized**. Examples where participants felt judged and had a desire to alter or hide their behavior included when they didn't follow an expected schedule, when they had not changed activities through several labeling time periods, and when they became aware of open-close duration, such as opening the fridge "too long" or washing hands "too briefly." They typically assume certain open-close events, such as the opening of a drawer with exercise equipment, will expose specific behavioral compliance information. While visual reminders of the sensors may have heightened these feelings, one participant noted that it was difficult to stay focused on more than one sensor type (video, audio, etc.) at once. There are also considerable individual differences in responses to being observed, with some participants seeming unconcerned, while others express feelings of being judged or disrupted.

11. Simple sensors can also **provide information about *how* an activity is performed**, and this may suggest opportunities for interface interaction. In these initial studies, we are seeing qualities of activities that may be significant, such as the prevalence of "false starts," activity overlaps, idle time, and redundancy. For example, trips to the freezer or refrigerator almost always involve two open-close events, as something is taken out, set down and used, and then put back (think milk, mustard, ice); this would be important to an HCI designer wanting to break down a message into smaller chunks, repeat a message to improve the chance that it will be noticed, or reinforce a message that may be operating on the user on a more subconscious level.

12. **There is no normal week**. Participants consistently indicated that the proposed installation period would be uneventful and routine, but we have found ourselves recording examples of altered and variable patterns due to such circumstances as job loss, diet change after diagnosis of an allergy, holidays, illness, guests, pet illness, changes in the weather, a sudden business trip, taxes coming due, and preparations for a new roommate.

LESSONS APPLIED

We are currently working on the next generation of sensors for the portable kit. We carry forward our initial design criteria of having many, inexpensive, simple sensors that can be installed by non-experts and that produce low-bandwidth data for robust recognition algorithms. We are also, however, applying these "lessons learned," to make the portable kit more responsive to the experimental requirements of home investigations.

Table 1. Design changes between our first version and next generation environment sensors.

First version	Next generation
3 points of contact	1 point of contact
Synched at sensor	Synched centrally
Registers on open-close connection	Registers on directional motion
LED signals event	No signal on sensor
Additional event information from open-close duration	Additional event information possible from velocity, direction of movement, distance of movement
Scheduled experience sampling	Event-triggered experience sampling

Table 1 summarizes changes in design features between the two versions of the sensors. The new sensors are accelerometer-based and use radio frequency (2.4 GHz) to broadcast an ID to a central receiver in real-time when directional motion is detected. The sensors do not require the alignment of components, such as with the open-close circuit, because they consist of just one element that is affixed to the part of the object that moves. In addition to detecting movement on objects with mechanical open-close states, they can detect directional movement in carried objects, such as the remote control, pushed objects, such as a chair, or vibrated objects, such as a couch cushion. In their initial form, they will only provide a signal that indicates a motion threshold in the appropriate direction has been reached. It is possible that they may be extended, however, to output information about velocity and distance of movement to provide additional clues about how the action is performed (e.g. a slammed door). In their default form, they will non-obtrusively record movement, without the signaling of an LED, but given their ability to transmit real-time, it is possible that output devices, including experience sampling on the PDA, could be set to listen for and respond to events. Thus a participant could be asked what he/she is doing when a chair is moved or be given a message when the refrigerator is opened.

This next generation of sensors represents will improve the volume and type of data we can collect and with less burden to research participants and experimenters. These sensors will be evaluated through a similar process of deployment in real homes and are available to other researchers to try.

ACKNOWLEDGMENTS

We thank our participants for having us into their homes and being patient with our initial efforts at capturing their everyday experiences. This work was supported, in part, by National Science Foundation grant #0112900 and the Changing Places/House_n Consortium.

REFERENCES

1. Beaudin, J. From Personal Experience to Design: Externalizing the Homeowner's Needs Assessment Process, in Media Arts and Sciences. 2003, Massachusetts Institute of Technology: Cambridge
2. Bao, L. and Intille, S.S. Activity recognition from user-annotated acceleration data. *Proc. of Pervasive 2004*. Springer (2004).
3. Choudhury, T. and A. Pentland, The Sociometer: A Wearable Device for Understanding Human Networks. 2002, Massachusetts Institute of Technology.
4. Hindus, D. The importance of homes in technology research. *Proc. of the Second International Workshop on Cooperative Buildings - CoBuild'99*, V. Hartkopf, et al., Editors. 1999.
5. Intille, S.S., et al., Tools for studying behavior and technology in natural settings, *Proc. of UBICOMP 2003*. A.K. Dey, A. Schmidt, and J.F. McCarthy, Editors. Springer (2003).
6. Kidd, C.D., et al. The Aware Home: A living laboratory for ubiquitous computing research. *Proc. of the Second International Workshop on Cooperative Buildings - CoBuild'99*. 1999.
7. Morris, M., et al. New perspectives on ubiquitous computing from ethnographic study. *Proc. of UBICOMP 2003*. Springer (2003).
8. Munguia Tapia, E. and Intille, S.S. Activity recognition in the home setting using simple and ubiquitous sensors. *Proc. of Pervasive 2004*. Springer (2004).