SPECs: Another Approach to Human Context and Activity Sensing Research, Using Tiny Peer-to-Peer Wireless Computers

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Abstract. A small battery powered peer-to-peer proximity sensing platform that can be attached to people, places and things can be a valuable tool to conduct research in human activity sensing. Such a platform senses the subjects' presence and activities in a wide variety of contexts, for example home, car, work, or shopping. It eliminates the need for deployment and maintenance of prohibitively expensive infrastructure. The goal is to sense the activities of one individual at large in their world, rather than the activities of a group in a well-instrumented laboratory setting. Preliminary results with a real-world application are described.

1 Introduction

How should researchers explore pervasive applications if they can't afford to deploy pervasively the experimental infrastructure they need? This paper describes a platform we have built called SPEC, to support our research in human context and activity sensing.

1.1 Lessons from Earlier Work

In the early 1990s Xerox EuroPARC researchers started investigating how applications could benefit from knowledge of the user's activities [1] using Active Badges [2]. PARC, EuroPARC's sister lab, developed a more capable platform [3] to explore the systems issues in more depth and demonstrate the fundamental capabilities of what Weiser [4] coined "ubiquitous computing" technology. At EuroPARC a number of novel activity-sensing demonstrators were built, including Pepys [5] an automatic personal biographer, Forget-me-not [6] a personal memory aid; and a reminding system [7].

Although these groundbreaking systems showed considerable promise, conducting trials beyond the confines of the laboratory proved difficult and expensive for reasons we will detail later. Services that could be tested at work were not available in other contexts outside work. Many memory problems like, "What was the name of that

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person I met on the airplane last week?” involved accessing information from, in, or between non-work contexts. So Forget-me-not for example – a memory aid that could only be used at work, and then only to recall work events was frustratingly difficult to evaluate.

Pepys and Forget-me-not provided continuous service through a series of wireless base stations connected to a central server. Having to connect each base station to a server, albeit via a network, made deployment extremely time consuming and expensive. Connecting to distant locations, like homes, or mobile locations, such as our cars, incurred significant telecommunication service costs, and required expert knowledge of network and security systems.

Active badges achieved a uniquely useful balance between sensing-range, battery life, and wearability, capable of providing hassle-free service running into many months without human intervention. Larger, more capable devices are nevertheless less convenient to wear all the time, and need frequent recharging, and every recharge raises the possibility of the device being forgotten and left behind. At the other end of the scale, RFIDs are easy to incorporate into clothing, but the readers are relatively large, and have a short range.

We found our fellow researchers, in large part, quite willing to be subjects for experiments that had the clear potential to invade their privacy. However there were concerns voiced about accidental, unthinking, or perhaps insensitive uses of the accumulated data, which was all stored in a single centralized database. In larger installations where there were lower levels of trust some people simply opted-out, or quite reasonably wanted to see what they were revealing about themselves *before* their data appeared in the central repository. It became clear that this would be an issue for larger scale field trials.

1.2 Proximity Is Often Enough

Many location sensitive systems detect absolute position to some level of granularity using GPS, or cell-ID. To detect in real time who, or what, is nearby they update and then query a central database. If either sensing device is out of range of the locating or communications infrastructure (deep in a building for GPS, or out of the service area for cell phone-based location system), they won’t be able to determine that they are co-located. Noticing that two sensors are co-located if they are both in a moving vehicle can be complex – especially if each updates the central database relatively infrequently. But for systems like Pepys it was sufficient to collect in real time only a unique identifier for the nearby objects, for later resolution offline. The reminder application functioned quite well with a small pre-loaded cache of identity information.

2 What Is Needed for Sensing More Widely

We believe that many of the more successful pervasive applications, such as cell phones, are tightly woven into the fabric of *all* daily activities, offering continuous, mostly invisible support to literally anyone, in almost any situation, where and when the need arises. As researchers we want to explore these new opportunities, and experience living in a world where activity-sensing facilities are available in all parts of our lives, to assess the new opportunities, and their impact on human behavior. So we are trying to explore ways to deploy automatic activity sensing on a wider scale and we seek to provide *each individual researcher and their families* with technology to experience, explore, and ultimately expand how pervasive computing could impact everyday lives. We looked for solutions with the following features:

1. Low cost (<= $25), long battery life (>= 1 year), small size & weight (can be inconspicuously worn or carried in a pocket) with a consistent proximity sensing range (<= 5 meters).
2. Sensors can be deployed where they are needed: in offices, cars, homes, or even public spaces, enabling small-scale field trials.
3. Colleagues can incrementally deploy and maintain the infrastructure themselves with no requirement for centrally administered activity log or co-location database.
4. The implementation of proximity sensing should match the user's intuitive sense of proximity as closely as possible. For example, a person one floor above is not normally considered to be in close proximity.

3 Design Strategy

The most distinctive aspect of our strategy is that it aims to increase availability on a per-user basis, rather than for a whole community, or geography – to create a *personal pervasive system* technology.

Our approach employs a collection of identical lightweight portable proximity sensors, called SPECs, designed to support the kinds of tasks we described earlier. We expect our colleagues, and eventually our users to deploy SPECs themselves, dotting them around in places they frequent, attaching them to objects, or wearing them.

Fig. 1. SPECs deployed by Kyle on the garage, backpack, scooter, and himself.

Although our goal is to create a platform for investigating a range of sensing technologies, we decided that our first prototype would only sense the proximity and identity of other nearby SPECs. This "what and where" information would be captured and acted upon autonomously, or uploaded later to a server for offline analysis. To further simplify things, and inspired by Factoid [9] and Pollen [10], device discovery employs an extremely basic peer-to-peer protocol and makes no reference to a central database, or wide area wireless network.

Each SPEC broadcasts a unique 32-bit identifier (ID32) every 2 seconds (to conserve power this interval is increased automatically when the set of SPECs in proximity isn't changing). They also listen continuously for the ID32 broadcast from nearby SPECs. When a new SPEC is sighted, a sighting record is created, time stamped with the start time, and stored in a history. Each record describes an interval during which a particular ID32 was repeatedly sighted. If sightings cease for more than a specified interval (2 minutes in the current system), then the sighting record is time stamped with the end time and closed. As we shall explain shortly, the sighting history can be analyzed locally to see if the user should be alerted to any noteworthy events, or it can be uploaded, via a SPEC portal, to an internet-based service for off-line analysis, archiving, etc.

A very simple sighting history pattern recognizer is used within SPECs to detect noteworthy situations. The pattern recognizer uses a byte code form that is downloaded to the SPEC by a portal. Once downloaded the pattern recognizer runs independently within the SPEC. The pattern language is declarative and consists mainly of time interval and ID set operations. Functions are available to find particular sightings in the history. Two of these functions are called `first` and `last`. They take two parameters, an ID set and a time interval, and return the first or last sighting of any of the IDs within the time interval. Functions are composed to create reminder expressions. If the expression result is true or a non-empty ID set then the reminder is considered active. Patterns can be defined and given names using a simple XML name/value structure. For example, the pattern to detect when a SPEC with ID 3 has last been seen for more than 5 minutes in the interval from 1:00 to 2:00 is:

```
<define name="LastSeen" value="duration(last({3}, [1:00, 2:00])) > 5m"/>
```

We anticipate that more advanced applications *will* want to make occasional connections to Internet services to archive sightings, process them into a more intelligible form, invoke other actions, or download new search tasks. To do this SPEC-portals provide mobile SPECs with the means to upload sighting history. Portals also provide a time service enabling mobile SPECs to set their real-time clocks, and a means to download patterns to support real-time applications.

We have given high priority to small size and battery life and in consequence, sacrificed communications and computational power, storage and user interface capability. We aspire to achieve power budgets in the prototypes that will allow small field trials of about a week to be completed without a battery change. Transferring data to infrastructure via portals is completely optional, but does provide a means to increase the number of contexts in which sensory information can be *immediately* relayed back to an individual's database for processing.

4 "Bring It Home Again" A Real-World Reminder Application

Kyle is a sixth grader with a number of ways to go to school: bike, scooter, walk, and car ride, and a number of different things to carry with him. With all those options it's no wonder that he sometimes forgets how he got to school on any given day, or to bring something home. As a consequence, on two occasions he forgot to bring home his scooter. By the time he remembered, the scooter had been stolen! We applied SPECs to the problem.

Fig 1 shows Kyle and his SPECs. A SPEC is attached to his scooter, the wall above its parking spot in the garage, he wears one, and has one on his backpack. He placed one on his desk at school. His wearable SPEC was loaded with a pattern, shown in Fig 2, designed to notice which articles he takes to school and to remind him if he does not return the same things home.

```
<define name="Home" value="{bathroom, kitchen, garage}"/>
<define name="School" value="{desk, 'bike rack'}"/>
<define name="Things" value="{backpack, bike, helmet, scooter}"/>
<define name="School Begins" value="8:30 a.m."/>
<define name="Dismissal" value="2:45 p.m."/>
<define name="Leave To School"
 value="end(last({garage}, [,'School Begins']))"/>
<define name="Leave To Home"
 value="end(last(School, [Dismissal, ]))"/>
<define name="To School" value="['Leave To School',]"/>
<define name="To Home" value="['Leave To Home',]"/>
<reminder name="Forgotten"
 value="retain(Things, 'To School') - retain(Things, 'To Home')"/>
```

Fig. 2. Kyle's reminder pattern.

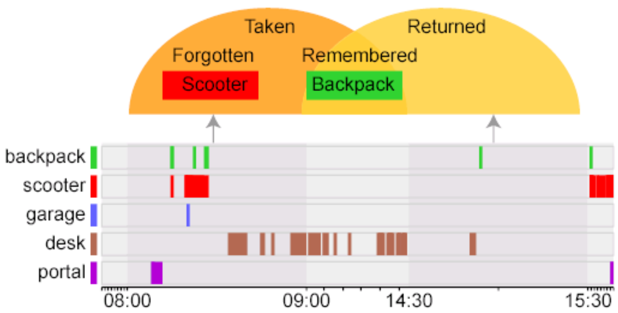

Fig. 3. Sighting records from the SPEC Kyle wore on a 'forgetful' day.

A chart of the sighting records from a forgetful day is shown in Fig 3. The various encounters can clearly be seen throughout the day: garage in the morning and afternoon, desk in between, backpack and scooter during travel times. The diagram above the chart illustrates how Kyle's SPEC keeps a watch out for any SPECs that accompany him in the period between his leaving the Garage and arriving at his Desk. In this example there are two: the backpack and scooter. The SPEC waits for school to be out *and* for Kyle to leave his desk. In this case it fails to see the SPEC Kyle attached to his scooter, the `Forgotten` reminder is triggered, and the SPEC LED starts flashing to remind Kyle he has left a tagged item behind at school. After some time, Kyle notices the reminder and returns to recover his scooter.

The tests ran for a couple of weeks. During that time he wore a SPEC the majority of the time. He constructed two different ways to wear it – as a necklace and as a bracelet. The necklace form turned out to be his favorite. It was quite a positive social experience for Kyle. Being a 6th grader wearing a high tech looking gadget produces a lot of positive attention. During the test period we had a number of issues to shake out, since this was the first real use of the devices in a natural setting. We had hardware issues involving the batteries and the enclosure, in addition to software issues with acquiring the time and knowing when batteries needed to be changed.

5 SPEC Prototype

Our goal was to develop a mechanism where objects could autonomously detect each other's proximity without reference to any additional infrastructure. At this stage we were focused on low-power, easy-to-implement solutions. With our experiments in mind, we estimated that that a coin cell battery life of one week was an absolute minimum requirement for prototypes that would be used to test our ideas. However, we wanted to make sure that the basic design could be engineered for year lifetimes at some point in the future. Several different underlying technologies could be used. For our initial prototype, we only considered two *proximity detection* mechanisms: radio (RF) and infrared (IR).

The challenge for proximity detection is finding a very low-power way for devices to signal to each other. Experience with Active Badges which transmit a very short identification IR pulse every few seconds, had demonstrated that lifetimes in excess of a year could be achieved for transmission only. But base stations that receive Active Badge signals are powered from the domestic supply. In contrast SPECs, all of which are identical and potentially portable, must both send and listen, and it soon became clear that *the challenge for the power budget is continuous listening*. A simple analysis showed that from a power perspective, domestic IR, the kind used for appliance remote control, offered the best off-the-shelf solution to the continuous listening problem.

The IR detector that is currently being used, a GP1UD261XK, typically consumes 150uA. The output of the detector is low when a 40kHz carrier is detected. This signal is used to interrupt the microcontroller whenever it changes. To minimize power consumption, the microcontroller and other components sleep except when processing IR detector changes. SPECs send their ID using a 100mA IR LED using a Manchester encoded signal over a 40kHz carrier for 25ms. This is done at a rate somewhere between 2 and 30 seconds – depending on how often the set of SPECs in proximity are changing. Assuming an average rate of 15 seconds, sending consumes about 50uA on the average. We are currently using 150mAh coin cells in our prototype, which results in a lifetime approaching one-month. Stationary SPECs could use AA cells that should result in approximately a two-year lifetime.

In contrast, the best off the shelf RF receivers were in the 2mA range. Thus their power consumption is about 10x that of IR, resulting in a corresponding $1/10^{th}$ the battery lifetime.

5.1 Predictable Discovery

But low power was not the only reason for choosing IR. Considering our proposed applications, it seemed important that the SPEC's model of what was nearby should closely mimic the user's model. For example, if we wanted to recall a situation from the past, or if we wanted to set up a reminder for some future event, then the user would need to have a good model of what people, places and things the *computer* was likely to sense. With an RF-based technology the shape of the field is difficult to predict without special instrumentation, and can fluctuate unpredictability depending on what other things move through the field. So a RF-based proximity detector might detect a person, or thing in an adjacent room that was invisible to its user. This could lead to very confusing behaviors. Since IR does not pass through walls and has propagation characteristics similar to visible light, it is much easier for a user to predict what things the computer might, or might not be able to sense. However, we can recognize that there are clearly situations where being able to sense the proximity of things that you can't actually see could be very useful.

IR is has its own set of issues. Transmission follows line of sight and can be obscured by obstacles like furniture or clothing, or simply by being pointed in the wrong direction (although IR is also good at reflecting off many surfaces, such as white walls, and thus does have some diffuse characteristics also). Bright sunlight or fluorescent lights also easily confuse IR. Some IR solutions, such as IrDA, are designed for short range and are highly directional. Remote control IR detectors and emitters have components that are less directional and have greater range. Given that ease of implementation, size, and power requirements were top of our priority list, and given encouraging results using IR from other research projects, we felt remote control IR was the best compromise for our initial pragmatic prototype.

5.2 Hardware

The current SPEC prototype, shown in Fig 4, uses a PIC18F252 microcontroller and a real-time clock for time stamping observations, which it can store in 32KB of memory accessible over an I2C bus. It communicates with other nearby SPECs using a 40kHz infra-red carrier with OOK at 2666 baud and Manchester encoding giving an effective data rate of 40 32-bit words per second, and a range of 4-8 meters. The current user-interface uses a single green LED and a single button. It has auxiliary output provision for driving a pager motor, or beeper. The I2C header can be used to connect additional circuits, such as sensors. The *debug header* is used during development for loading and debugging the software kernel. Using off-the-shelf components the electronics package measures 40x15x14 mm, including two 11.6mm diameter coin cell batteries that are held in place by metal clips underneath the circuit board. Total cost is approximately $25, which includes the components, batteries, circuit board, and enclosure.

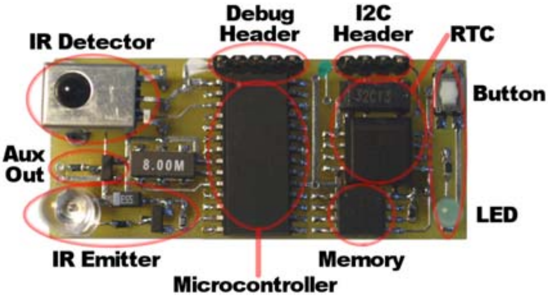

Fig 4. The current SPEC prototype board

6 Conclusions

It's a bit too early to claim that this approach to gathering context data is a success, but the results above are very encouraging. The main thing to note is *that installing the infrastructure is as simple and speedy as it sounds*, and that this approach does indeed allow us to sense more parts of our lives, including expeditions into the outside world away from work or home. Battery life allows continuous operation for useful periods. The database is optional and distributed - holding only the data for a particular set of users. We are beginning to see that SPECs can provide a valuable source of field study data for future design work and may indeed be a valuable resource for behavioral science field studies in general.

It seems that an ideal proximity sensing technology for this type of applications is currently not available off the shelf and remains an open research opportunity. The two most likely candidates suffer from having to be visible (IR) or having an unpredictable field (RF). Power consumption and battery capacities are major challenges as well.

We anticipate that our next step will be to explore using RF for proximity detection, and to add sensors to detect motion, etc.

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