A Flexible, Low-Overhead Ubiquitous System for Medication Monitoring

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Abstract. For ubiquitous computing systems to gain acceptance, they must be functional, flexible, robust, easy to use, and meet demonstrated user needs within actual user physical contexts and usage patterns. This paper focuses on a particular domain for such systems, that of home medication taking. We conducted a study to derive user needs and settings for that domain, and present the results. A prototype system is presented for home medication taking, designed to meet those requirements and goals: be more functional, more flexible, easier to configure, and a better fit with exist contexts of use.

1 Introduction

Traditionally, researchers have judged computer systems primarily on their speed, their functionality, and the ease of use of their user interface. There is increasing recognition that the bar should be raise, cf [1, 2]. In addition to these previous metrics, systems need to be judged on characteristics of robustness and flexibility, such as their flexibility of deployment, time to deploy, time to alter or re-deploy, training required to configure, and so forth. These new metrics are even more important for ubiquitous computing (ubicomp). Ubicomp systems often need to support users located in various (and varying) physical settings, and must integrate the system into those settings in a natural and unobtrusive way [3], rather than requiring the user to come to the system as is done in traditional computing. In addition, recent work suggests that ubiquitous systems need to be even more trustworthy and easy to use than their desktop counterparts to be accepted [4].

In this paper, we present an investigation of a Ubicomp system to monitor and assist medication taking in the home, a system grounded in a user survey whose results are also presented. The heart of the system is a portable monitoring Pad which combines Radio Frequency Identification (RFID) tags with a sensitive scale to detect when people pick up and put down pill bottles, and measure how their weight has changed. The data from the Pad (and other such monitors) is then combined into a central database, and made available for analysis and integration by other Ubicomp applications. One simple application is shown, which uses a tablet display to proactively remind the user how many pills they need to take, of which medications, and when. We believe it advances the state of the art on a number of fronts:

- *Functionality*. The system can track the individual pills taken, and supports liquid medications.
- *Flexibility of location*. The system can be deployed in any room in the house, its only requirement being access to AC power (and even that could be eventually removed). No structural modification of the house is required. It can be redeployed at will.
- *Flexibility of integration*. The system separates its sensors from its database, and its database from its actuators, allowing any or all of those to "plug and play" with any other ubicomp systems nearby. This allows considerable flexibility in how the system can be tailored to fit the needs and contexts of different users.
- *Ease of configuration*. The system is initialized via a single button press. Second, the system is designed so it can read its medication database from the upcoming "smart labels" proposed for pill bottles (labels which contain RFID tags in addition to other labeling information). Third, a novel user interface technique is presented allowing users to easily specify their medication-taking patterns. A simple grammar expresses the patterns, with physical cards used to represent terminal symbols in the grammar. Users place a few cards on the Pad to construct sentences in the grammar. Despite its functionality and seeming complexity, the "user manual" is less than a page, much of which consists of pictures.
- *Matched to actual use*. We conducted a user study to determine how people actually use their medications in the home, and used that to inform our design. We present the sometimes surprising results here.

We proceed by motivating and discussing the application area, and highlight the state of the art. We then report selected results from a user study which informs the design of such systems in actual home settings. Our system is then presented, and discussed in detail. We close with a final discussion and suggestions for future work.

2 The Value of Monitoring Medication Use

By "medications", we mean any packaged item taken for health reasons, including vitamins, aspirin, cold medications, glucose tablets, and so forth. Medication taking forms a significant part of our daily lives. To ground this significance in numbers, to give some idea as to the issues and challenges in parts of this space, consider the following recent U.S. statistics [5, 6, 7, 8, 9]:

- 55% of the elderly fail to comply with their medication regimens, with 26% of those errors being potentially serious.
- 50% of all filled prescriptions are taken incorrectly.
- 23% of nursing home admissions are due to noncompliance, costing $31.3 billion dollars per year, and affecting 380,000 patients.
- 10% of hospital admissions are due to noncompliance, costing $15.2 billion per year, and affecting 3.5 million patients.

- Medication errors account for at least 7,000 deaths, and at least 770, 000 injuries each year.

Clearly, the arena of medication monitoring encompasses a number of significant problems, from severe errors (7,000 deaths) to moderate errors (50% of all prescriptions filled are taken incorrectly), to less catastrophic but still annoying issues (55% of the elderly fail to comply with their medication regimens, people of all ages struggle to remember to take their vitamins). These problems will become more significant as average lifespan increases and the range of medications grows – any solutions which can have small effects, even in corners of this space, are of interest.

We believe that this domain is well-suited for ubicomp solutions. As we make specific in section 4 and elsewhere [10], medication taking occurs at various locations, in various contexts, and often by those most averse to computer technology (the elderly). As people rarely take their medications when next to a desktop computer, desktop solutions are of marginal utility in this space – ubicomp systems integrated in to existing locations in existing homes can provide a unique value. Finally, many different types of reminding / prompting / monitoring are possible (as discussed in section 4), with all the actuators present in a home available for those proactive reminders; a fertile environment for the proactive solutions proposed by many, cf Want et al. [11]. We therefore believe that unobtrusive, low-overhead, easy-to-use, flexible Ubicomp solutions are a desirable path to pursue.

3 Related Work

There are commercial systems employed for pill tracking. At the high end, there are large and expensive units used primarily by caregivers (the "MD2" [12] is a representative example), where an administrator pours pills into a set of slots in a stand-alone unit. The pills are then dispensed, one at a time, by pushing on a large button. Either the housing is rotated so the dispensing slot lines up with the particular type of pill to be dispensed, or there are a set dispensers, one per slot. The pills are then dispensed, one at a time, through the slot. These systems can accurately count the number of pills dispensed, but their interface is so restrictive (requiring pills to be taken out of their original containers and poured into individual slots, the pills to be dispensed one at a time, the slot opening manually adjusted so that only one pill comes out at a time, and often requiring the housing to be rotated to the correct slot each time), and the units so expensive, that they are rarely used in the home.

At the low end, there are containers like "7-day pill reminders", plastic cases with 7 compartments which serve simply to provide users with an auxiliary container in which they can time-order their pills. The container doesn't know which pills are in it, when they should be taken, or when they have been taken; no monitoring or integration is possible. However, their low cost and ease of use makes them fairly popular.

For ubicomp systems within the home, the antecedent to our system is the innovative and influential "Magic Medicine Cabinet" of Dadong Wan [13]. In this prototype, a special-purpose medicine cabinet was created. It used face recognition to recognize a user, and RFID tags to recognize when that user took pill bottles out of the cabinet. A flat-panel display, a touch-sensitive screen, and a speech synthesis unit were all integrated in to the cabinet, used for user input and to provide feedback and reminders to the user about their daily medication.

Our system shares the same application space as the Magic Medicine Cabinet (Ubicomp systems to assist medicine taking), and one similar technological component (the use of RFID tags on pill bottles). After that, our systems diverge. Rather than the "heavyweight" point-solution approach embodied by the Magic Medicine Cabinet (a special-purpose unit built into a wall of a house, with multiple integrated and expensive output units), we take a "lightweight" integratable approach. Based on our user study, we want to bring some of the advantages of the Magic Medicine Cabinet to real homes, allowing users to situate and use them as best fits their particular home context. Our system requires no structural modifications, can be located at various places throughout the house (this is particularly important as our user study showed that only 4% of our users use only a medicine cabinet for medication storage), can have as many or as few actuators and output modules as desired, can have its data integrated in with that from other sensors in the home, and is easy to build, configure, deploy, and re-deploy. We discuss these in detail in future sections.

4 Defining the Space

When designing any system, it is desirable to know as much as possible about the desired user population and its usage characteristics. This is particularly true in the case of ubicomp systems, where "the mountain must come to Mohammed", the system should unobtrusively and naturally integrate in to the users existing physical environment. In our case, our project started with a focus on people with early stage Alzheimer. From interviews with caregivers and relatives we identified a need for a system to passively monitor the medication-taking of persons with early stage Alzheimer, and report it to interested parties. As the project developed, it became clear that it would be more broadly applicable to anyone who took medications at home. As we broadened the system for this much larger space, rather than extend our design based solely on intuition and personal experience, we decided to do a user survey.

The details of the survey and a full set of results can be found elsewhere [10]. Briefly, we had 53 participants complete a 22 question questionnaire regarding their medication use. We tried to achieve demographic variety. The participants ranged in age from 18 to over 70, with a median of 31-34. Participants lived in 8 different states, though all were in the U.S. Participants took at least 1 type of medication, and at most 12, with a mean of 4.51. 61% were female. Since participants were over 18, and only answered questions about their own personal usage, children are not represented. We list some of the most salient and/or surprising results here:

- *Many rooms are employed*. No single primary room for medication keeping or taking emerged, although two locations (kitchen and bathroom) did predominate. Furthermore, for those participants who kept their medications in only one location, four different locations were mentioned.
- *Many locations are used within a room*. We were curious to see whether we could make any simplifying assumptions as to where medications are kept, within the room. There was very little consensus. Many medications are kept on a shelf, many are kept in plain sight on a counter-top, many are kept in a dresser, and some are kept in none of those locations. Each location has different industrial design requirements – different heights and widths, different access to electricity, etc. This suggests that the monitoring system either needs to be very small (so it can fit in as many form factors as possible), or a system should support multiple sensor devices (optimized for different locations), or both.
- *Medicine Cabinets are an unsatisfactory single monitoring point*. To our surprise, only 26% of participants use a medicine cabinet at all, and only 4% used a medicine cabinet as their sole location for medication storage.
- *Packaging implications*. 86% of the medications were in bottle form, implying that systems should focus most of their energies on this form. A distant second, but still significant, were blister paks (11%).

- *Multiple users per location are common; multiple users per bottle are not.* 34% of participants share the medication space, but only 7% of participants share any medication with anyone. This suggests that while systems should support multiple users, it may be an acceptable simplification to associate a medication with exactly one user – "heavyweight" recognition technologies such as face recognition and personal badges may not be necessary.
- *Liquid medicines are rare*. Only 1% of the medications taken come in liquid form. While this number may be so low because we didn't track children's medications, if this holds in general this implies that a system which measures changes in weight can "coarsen" its monitoring to pill-level; the fine weight changes allowed by continuous liquid flow need not be tracked.
- *Removing a pill does not imply taking a pill*. 26% of participants take pills out of their original containers and into an intermediate one, such as a 7-day pill reminder. This implies that systems should evolve which can track mixed pills in such containers. Failing that, when combining this fact with the fact that false positives can happen in other ways (e.g. the user removes a pill and then forgets to take it), designers should recognize that such systems will often throw "false positives", thinking a user took a medication when in fact they did not. Alert activities and proactive reminders should take this into account when determining whether they should intervene, as per the framework suggested by Horvitz [14].
- *There are many opportunities for proactivity*. While the levels of interest varied, the following opportunities for feedback would be often applicable:
  - prompted as to when to take a pill (64%)
  - told which pills they had taken that day (50%)
  - reminded of activities encouraged/discouraged after taking a pill (46%)
  - told of possible side-effects (42%)
- *A wide range of proactivity levels is necessary*. For each of the places where proactivity *can* be employed, there was a wide range of feedback as to the extent to which it *should* be employed. First, purely passive medicine monitoring for a 3rd party would have some usefulness for 79% of participants. Second, as discussed above, the accuracy of such systems will probably not be very high for some time – the only thing nagging is inaccurate nagging [14]. Third, we saw a wide range of answers for all of the activities mentioned above. We cannot conclude that any one proactive activity is a "must-have". Fourth, a significant number of participants (57%) sometimes deliberately choose to *not* take a medication. Putting all these together, we conclude that a monitoring system must accommodate a wide range of possible reminders (including none at all), conveyed in a wide range of mechanisms.
- *Medication reminders need multiple display formats*. Users maintain at least three different mental images when thinking of a medication; thinking of the shape of the bottle, thinking of the shape of the pill, and thinking of the name of the medication. Each has a significant number of users who use it exclusively (19%, 11%, and 49%, respectively). Any system which doesn't support all three modalities may alienate a significant percentage of users. We see again the need for flexibility within users, as roughly 19% of participants indicated they employ

more than one form, suggesting different forms are used to remember different medications.

5 The System

Summarizing the results from the user survey, and in accordance with the design philosophy discussed in the introduction, we pursued the following previously unaddressed design goals, in addition to the previous goals of functionality and accuracy:

- *Flexibility of location*. The system should be locatable in multiple rooms, and in multiple locations within rooms.
- *Flexibility and multiplicity of proactivity*. The system should support many different levels of proactivity, allow users to specify those levels, and allow each level to express itself as flexibly as possible (e.g. support various actuators, including more than one simultaneously).
- *Flexibility and multiplicity of sensor systems*. The system should support multiple packaging modes (e.g. bottle, blister pak, pill reminder systems), and multiple sensor systems (e.g. two in the bathroom, one in the kitchen, one in the bedroom).
- *Low-overhead configuration*. The range of possible medications, possible user patterns of medication-taking, and proactivity scenarios can create a system which is difficult for a user to control and configure. The system should minimize the amount and complexity of user configuration.

At the highest dimension of our system, this implied decoupling the various components of the system. The system accordingly consists of three orthogonal entities:

1) *Sensors:* A set of one or more types of sensing devices, and zero or more instances of each such device. While our current implementation only uses one type of sensing device (the "Pad" discussed in detail later), which can monitor bottles, we have successfully tested using multiples of that device. As 86% of users only use bottles, this seems an acceptable first generation limitation.

2) *Database:* A database that can be fused with other data provided by the environment, to allow multiple ubicomp applications to interpret the data and possibly fuse it with data reported by other sensors. For example, by fusing the medication information with that reported by sensors in the kitchen, a system could sometimes detect whether the user had eaten before/after taking a pill. By fusing the sensors with load sensors in a bed, the system could detect if a user is going to bed before taking their night-time medications. These are only a few of the many possibilities. We currently use a Microsoft Access database, accessed by a JDBC-ODBC driver.

3) *Actuators:* A set of zero or more actuators, which proactively act on the information supplied by the sensors (medicinal and otherwise). This set can be empty; our questionnaire showed, for example, that a system which is purely passive and serves solely to report the medicine information to a 3rd party such as a doctor, caregiver, allergist, trainer, etc., would have some use for 79% of the participants.

Even when proactivity or reminding is to be employed, there are many possible actuators. Some users may prefer no actuation. Other users may prefer the actuator located remotely, for example an actuator which alerts a doctor or caregiver if too few or many required medicines are taken (this scenario would be useful for early-stage Alzheimer patients). Other users may prefer a reminder displayed next to their medicine, as in the earlier work [13]. Others may prefer more “ambient”, unobtrusive, reminders, such as the Ambient Orb or Ambient Healthwatch [14]. Yet others may prefer an electrical reminder, for example in the night-time scenario mentioned above the system might flash the lights near where medications are kept (wherever that may be) to remind the user to go there and take their medications. Finally, the same user may prefer different actuators for different medicines, and/or more than one such actuator for the same medicine. For example, a user may wish to be reminded when it’s time to take a given medication, and have their doctor notified if they don’t take it. This is a large and fertile area for future exploration. Our system therefore allows such flexibility, but the overhead is low – an application which only wants to monitor sensor data and act based on that can do so very easily.

Within this general system architecture, we have created two specific artifacts: a medicine pad for sensing the medication activity, and a tablet display for optionally displaying proactive guidance and reminders. We now discuss each in turn:

5.1 The Monitoring Pad

The heart of our system is a pad which is designed to detect (a) *when* bottles are lifted off and put back, (b) *which* bottles are so moved, and (c) *how many* pills are removed from the bottle in between. A picture showing the pad as it appears to the user is in Figure 1, a functional diagram is in Figure 2.

Figure 1. the Monitoring pad, as viewed by a user

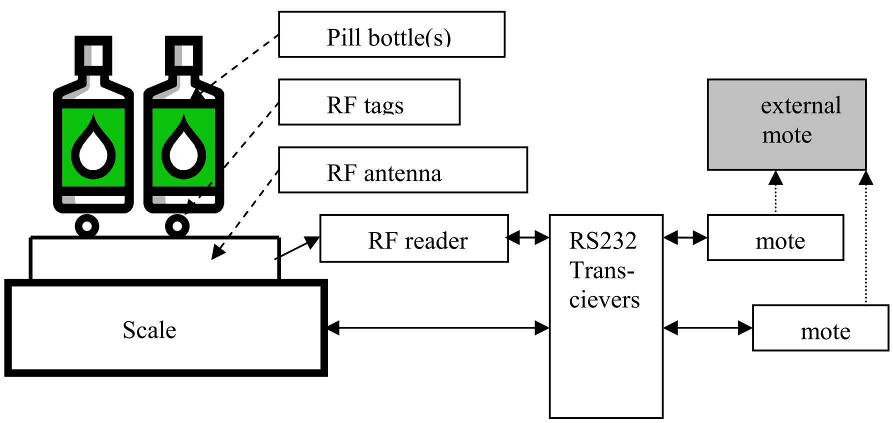

Figure 2: the pad functional diagram. Bottles with RFID tags are monitored by an RF antenna, and a scale. Their data is read by small processors with radios (the motes), and then sent wirelessly to the outside world for further processing

To detect when and which bottles were moved, we use passive RFID tags. RFID tags are an increasingly popular technology for tagging items which allow an *N*-bit number to be associated with an item (*N* is typically 64 or more), which can be detected without line-of-sight (unlike bar codes), and which require no power source on the tag. By using RFID tags, we align with an emerging movement in the pharmaceutical industry to place such tags on pill bottles as part of the label, instead of or in addition to the barcode, cf [16,17].

We chose 13.56 MHz RFID passive tags. This has a number of advantages:

- *Ubiquity.* This is the most common type of RFID tag, complying with an international ISO standard, allowing us to "plug and play" between multiple tag and reader vendors for our application. For example, we are currently using TI "TIRIS" tags, which are detected by a SkyeTek "SkyeRead M1" reader.
- *Collision detection*. The 13.56 MHz tags support collision detection, meaning that one antenna can detect and report multiple tags within its tag range. This let us use one single antenna to cover the entire pad. Without this ability, a multiplicity of small antennae would be needed, one per pill bottle, which would add significantly to the cost and complexity of constructing such a system, and reduce the usability, as users would have to be careful to place each bottle in the "sweet spot" of each antenna.
- *Size*. The tags come in a variety of form factors, one particularly interesting form factor is a thin circular disk, roughly 12 mm in diameter (see figure 3). Such a tag fits unobtrusively on the bottom of pill bottles.

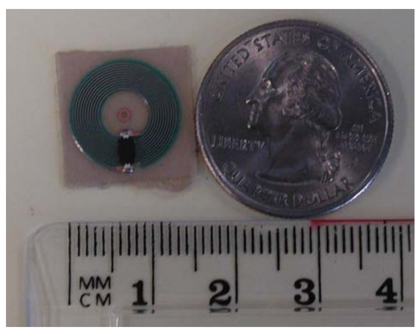

Figure 3: A 13.56 MHz RF tag suitable for pill bottle bottoms

- *Potential for replication*. Some tags, including the ones we chose, are read-writable. One could take the per-bottle data obtained by the system (e.g. # of pills taken today) and write it to the tag, instead of or in addition to transmitting it to a central database. This replication would allow greater functionality when the wireless link is inoperative.

To detect the tags, we chose a Skyetek "SkyeRead M1" reader, as it had the smallest form factor and an easy to use interface protocol. The reader is attached to a custom-made antenna. The antenna is rectangular (18 cm by 19 cm), is made from 0.6 cm wide copper tape, has 10K Ohm resistance, and 120 pF capacitance. The antenna is invisibly placed on the underside of the top surface of the pad.

This allows us to detect when a bottle is lifted off/put back, but not to detect individual dosage. To do this, we merged the RFID sub-system with a commercially available fine-precision digital scale, the "Ohaus II SC-6010".

There is a design trade-off when using such scales. The greater the weight capacity of a scale, the less precise it is. We needed a scale which was precise enough to detect most pills, but with a weight capacity great enough to handle at least 4 average pill bottles simultaneously. We wound up choosing a scale which is accurate to within 100 mg, and with a weight capacity of 600 g. While there are pills which are too small for it (100 mg is roughly the weight of a "tic-tac"), and there are sets of bottles to heavy for it (several large jars of vitamins, for example), we believe this is a good middle ground. This is another example of why such a system needs to be flexible; different users with different medications may wish to use different scales.

To make our system as easily reproducible as possible, we wanted to use as many off-the-shelf parts as possible. In this goal, we largely succeeded. Our system only has one custom part, a small PCB board used to unify the various DC power supplies needed by the system, and do the RS232 transceiving. However, using an unmodified off-the-shelf scale has its disadvantages. In particular, the scale is rather large. Since we wanted to treat it as a "black box", we did not tamper with it. This was responsible for the great majority of the "footprint" of the pad, which as currently constituted is 26 cm by 31 cm by 11 cm. The device could be made much smaller in future generations, if smaller scales are used, and/or the scale is broken apart.

One other design challenge was posed by the integration of an RFID reader with a scale of this sensitivity. The energy emitted by the RFID antenna when it is seeking for tags is enough to disturb the scale circuitry. We found that we had to place the RFID antenna 4 cm above the scale, and shield the scale, to prevent this interference.

The third component of the Pad is a communications device. We wanted to keep the sensor system de-coupled from any higher-level proactive application. We therefore needed a way to send the sensor data (the tags seen, and the weight on the scale) to a central database. We do this by using two Berkeley motes [18] to wirelessly transmit the sensor data to an external receptor. The wireless transmission protocol employed by the motes supports having multiple pads within range of each other.

One mote monitors the scale, and another monitors the RFID reader, both via a serial port connection. We would have combined this functionality into a single mote, but the current generation of motes only has 1 serial port. The motes then wirelessly transmit their data whenever the scale weight changes, and furthermore the RFID antenna is only activated when the weight changes. By having the RFID subsystem quiescent nearly all the time, we drastically reduce energy consumption, which will prolong system life for future pads which have no external power source. The amount of radio traffic is also very small. This does create a bit of a user interface lag, however, as it takes the system a few seconds to update when a bottle is lifted off/put back.

The fourth component of the Pad is a custom PCB board to unify the power supply to the previous components. The RFID reader requires 5V, the scale requires 9V, and the two motes each require 3.3V. We didn't want to require users to plug in 4 AC-DC converters to power each pad, and so made a small (4 cm by 4 cm) PCB board which serves to distribute power to each component.

The fifth, and last, component of the Pad is the housing. We chose a simple off-the-shelf box from a "Storables" chain store, and used a Dremel tool to cut a hole in it that the scale fits into. The RFID antenna is then attached to the underside of the box. We picked the box because of its "homey" wicker look. In hindsight this was an unfortunate choice, as the "pseudo-wicker" turned out to contain metal cables running through it for structural integrity, which caused several problems. First, this caused transmission problems with the Mote radios. We solved this by snaking a small antenna out of the back of the unit, but in the future we would choose a box without metal in it. Second, the metal cable along the top interfered with the RFID antenna; we had to remove that cable. In the future, we would use a different housing.

By so encapsulating and connecting the components, the Monitoring Pad is nearly completely stand-alone. A user simply picks one up, plugs it in, does a one-time press of an "initialize" button, and the system is off and running.

5.2 The Display

As mentioned earlier, to make our system as "plug and play" as possible, it was designed to work with any number of output actuators, including no actuators at all. In this case, the system serves to monitor and log activity, but gives no hints or reminders to the user. We have implemented one sample actuator to show the system "pipeline" in action.

Our sample feedback device consists of a Fujitsu Stylistic tablet, encased in a wood frame for aesthetic appeal. The device runs a web page that displays to the user information as follows:

1. When the user lifts a bottle off the Pad, the display reminds them of how many pills they are to take (if any).
2. When the user puts a bottle back, and pills have been taken, the display reminds them of any applicable post-medication suggestions (e.g. to eat, to stay out of the sun, etc.)
3. Otherwise, the display reminds them of which medications they have left to take in the current time window.

Figure 4(left) shows the display in use, placed behind the Pad. Figure 4(right) shows a close-up of a sample display – the user is being told that they need to take 3 Flintstones vitamins yet that day, and 2 pills of the Vitamin C they are holding.

Figure 4: the display in use behind the pad (left), and a sample message (right)

5.3 Initial Configuration

Reducing the time, money, and effort needed to initially install ubicomp systems or modify their behaviors is vital. Our system aims to be easily deployable and relocatable physically, by its encapsulated nature. The Pad is a self-contained box, which needs nothing more than an AC power outlet to function (and that could be easily removed by adding a rechargeable battery to the Pad), as long as there is a Mote anywhere within range to receive its messages. The Display is even more flexible. It may be kept in its housing or without, with external power or without, in the same room as the Pad(s) or without. It could even be kept in a different house, for example a concerned relative or friend could use it to monitor the medication-taking of a person of interest. Finally, the output to the Display is itself a simple web page; any other device with a preferable form factor which displays web pages could be used.

Our system also strives to be easily deployable in terms of the amount of data entry that needs to be done. There are two types of data the system needs, we address each of these in turn:

1. *Medicinal information*. For the system to function optimally, it needs a certain amount of information about each medicine – what its dosage weight is, what its name is, a picture of its pills (for user feedback), and so forth. As mentioned previously, there is a movement afoot to have pill bottles come with such information, via a standard EPC (Electronic Product Code), an RFID tag successor to the bar code. Once these systems exist, our system can use it. Another "flexibility" attribute of our system is that it will still work even if none of this information has been supplied.
2. *Patterns of use*. Users may wish the system to remind them when it's time to take a particular pill, or tell the system who to alert in case of mis-medication. Such information cannot be derived from the medicine type alone. For example, dosage amounts and/or frequencies can be a function of a person's age, weight, condition severity, other medicines already being taken, and so forth. The standard way for a user to enter such information would be via some sort of form on a web page, however we wished to explore other mechanisms for entering this information, as those types of users who use medication the most are those most averse to using the web (the elderly), and/or may not have access to a browser. Instead, our system allows user specification as detailed below.

5.3.1 A Tangible User Interface for Specification of Medication Use

As our system already has an RFID reader, we already have a way to receive additional information from a user. The work of Want et al. [19] showed how RFID tags can be used to indicate simple commands, and Camarata et al. [20] showed how IR-tagged objects can make command sequences. We combine and extend those works in our system, where users are given a set of RFID "Command cards" which they use to construct command sequences describing their medication use. Some cards serve to modify other cards, a new design attribute for tangible command interfaces.

As recommended by Fishkin et al.[21], we designed our grammar such that it would support defaults for virtually every parameter, and as in Camarata et al. [20] we designed it to be independent of spatial order – card A to the left of (or above) card B is identical to card B to the left of (or above) card A.

There are four groups of cards, as shown in Figure 5:

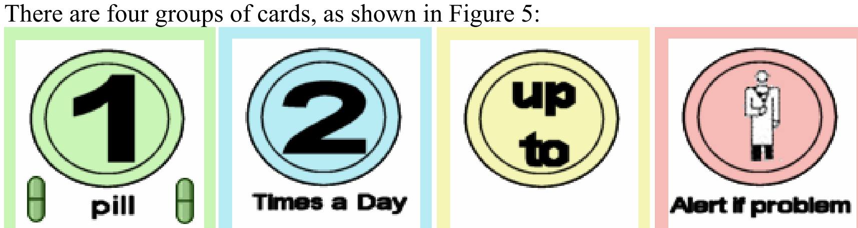

Figure 5: the command cards

- ☐ *Pill* cards indicate how many pills are taken at a time – one, two, three, etc.

- *Frequency* cards indicate how often a particular pill is taken – once a day, twice a day, etc. The “as needed” card indicates an unbounded frequency.
- *Range* cards modify pill cards, by indicating whether the number of pills is a lower bound (“take at least two”), an upper bound (“take up to two”), or both (“take exactly two”).
- *Notification* cards indicate who should be notified in case of a mis-dosage, for example that a caregiver should be notified if a particular medication isn’t taken.

To emphasize the different groups to the users, each group has its own distinctive border and central color.

Some dosage patterns that could not be accommodated by such a simple language (e.g. “take 2 of these a day, but 3 if after a heavy meal, and skip before going to the dentist”), but they are rare. This simple language accommodates 84 of the 85 dosages reported in the questionnaire (1 participant takes ½ a pill), and 123 of the 130 reported frequencies. Those outlying cases could be handled by making a few more cards.

We made the grammar very flexible to support naïve use. Each group has a default: “once a day” for frequency (the frequency reported 68% of the time by the questionnaire), “one” for Pill (reported 69% of the time), “exactly” for Range (reported 87% of the time), and no Notification. Most sequences of commands are valid, with only a few restrictions:

- At most one card from any group
- If a Range card is present, a Pill card must be as well.

When a command sequence is seen, it is applied to whichever pills are on the scale at that time. For example, figure 6(left) shows a very simple command, the user is indicating that they take 1 Vitamin C pill, twice a day. Figure 6(right) shows a more complicated command, the user is indicating that they take at least 2 of a prescription drug per day, and if they don’t, the doctor should be notified.

Figure 6: the Command cards in use

One implementation issue bears reporting. When users pick their command cards up off the scale, it is possible that they won't grab them all at once. Or, even if they do, that the RFID reader doesn't lose track of them all at the same time. In these cases, there will be some transitional command strings reported which are subsets of the desired command string. If the system acts on those strings, it bears the risk of altering the users' original intent. Accordingly, our implementation rejects any command string which is a subset of the last command string. While this can sometimes create frustration (the user puts down 2 cards, then realizes they only wanted 1), we believe that on balance it's a good trade-off.

The current cards are all unary operators, ones that modify a particular attribute for a particular bottle (or set of bottles). The grammar also easily supports other operators, for example binary cards like "don't take together" (establishing that medication A is not to be taken with medication B).

6 Conclusion and Future Work

A criticism of ubicomp systems is that "…almost no ubiquitous-computing systems work ubiquitously, or even in two places" [22]. Our system has tried to address this criticism, to help move ubicomp systems along the path from concept to compelling reality. We hope that we have shown a system which advances the state of the art along a number of dimensions: functionality, user interface, practicality, scalability, orthogonality, and feasibility – an easily deployable, flexible, powerful component of a Ubicomp system.

There are many areas for future work. From lowest level to highest:

- Within the Pad itself, there are many mechanical improvements that could be made, such as a smaller footprint, an internal power supply, fewer motes, and a better housing.
- On a system level, we would like to realize a system with multiple sensor types, for example a sensor system which detects when pills are opened in blister paks, such as the systems being developed by Cypak [23] or Med-ic [24], or that can work with 7-day pill containers.
- On an application level, we have done alpha testing in the homes of three members of the lab. While this has been useful, the next major step is to do user testing and evaluation in the field.
- Finally, there is a largely untapped field to explore in the area of the reminding and actuation networks – integrating multiple actuators, integrating multiple event sources with a fixed set of actuators, tuning the actuation network to a particular user, and so forth.

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