The Independent LifeStyle Assistant™ (I.L.S.A.): Lessons Learned

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Abstract

The Independent LifeStyle Assistant™ (I.L.S.A.) is an agent-based monitoring and support system to help elderly people to live longer in their homes by reducing caregiver burden. I.L.S.A. is a multiagent system that incorporates a unified sensing model, situation assessments, response planning, real-time responses and machine learning. This paper describes the six-month study of the system we fielded in elder's homes and the major we lessons learned during development.

1 Introduction

Historically, 43% of Americans over the age of 65 will enter a nursing home for at least one year. In spite of the financial and emotional strain placed on the family, a nursing home is often the only care option available when a loved one can no longer live safely alone.

We have been developing an automated monitoring and caregiving system called *Independent LifeStyle Assistant*™ (I.L.S.A.) [38, 44]. Researchers and manufacturers are developing a host of home automation devices that will be available in the near future. I.L.S.A.'s concept is to integrate these individual devices, and augment them with reasoning capabilities to create an intelligent, coherent, useful assistant that helps people enjoy a prolonged, independent lifestyle.

From January to July 2003, we field tested I.L.S.A. in the homes of eleven elderly adults. The I.L.S.A. field test was designed to complete an end-to-end proof-of-concept. It included continuous data collection and transmission via security sensors installed in the home, data analysis, information synthesis, and information delivery to I.L.S.A. clients and their caregivers. The test concentrated on monitoring two of the most significant Activities of Daily Life (ADLs)[1]: medication and mobility. All ADL-based monitoring was performed by family caregivers.

This paper describes the system we built, outlines the field study, and then describes the major lessons we learned in technology and usability; we touch only briefly on business lessons.

[1] ADLs focus on assessing ability to perform basic self-care activities and include eating, dressing, bathing, toileting, transferring in and out of bed/chair and walking.

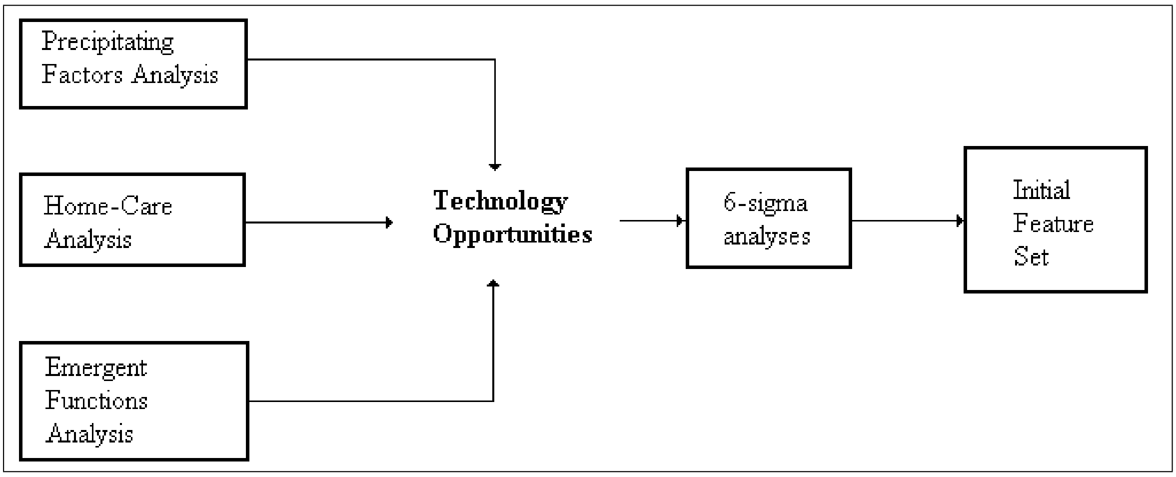

Figure 1: Identifying I.L.S.A. features.

2 Knowledge Acquisition and Feature Selection

Our knowledge acquisition activities were designed to identify the aspects of independent living that threaten continued independence for community dwelling elders. Our goal was to understand why elders cease to function independently so we could focus technology development on the key impedances to independent living.

The team identified assistance needs through collecting and analyzing information about precipitating factors, home care needs, and emergent functions. We then generated a list of 300 technology opportunities that might meet those needs. Using Six Sigma (6σ) analysis, we narrowed the list to 20 achievable items. These items became the initial I.L.S.A. feature set.

2.1 Precipitating Factors

We used a combination of resources to identify an initial list of the most common reasons elders leave their homes for care institutions. We reviewed gerontology literature and age-related web sites. We interviewed geriatric experts. We also interviewed Honeywell Labs employees who had recently served as a caregiver to an elderly parent. The team identified the following needs as having the greatest importance to both elders and caregivers.

- medication management
- caregiver burnout
- cognitive disorders (notably dementia)
- incontinence
- medical monitoring
- safety (notably falls)
- wandering
- mobility
- eating
- isolation
- transportation
- managing money

This list was used to focus data collection activities on the most significant reasons elders leave their homes. We designed a questionnaire, several interviews and targeted observations to gather more detailed data on these activities.

2.2 Home Care

We investigated home-care provided by health professionals to identify where formal caregivers most need assistance to provide quality health care that supports elder independence. In the investigation, we used a combination of surveys, interviews with home-care specialists and observations of home-care visits.

Surveys: We developed a survey for elders and caregivers to gather information about home environment, technology, and appliances in the home, as well as the technical savvy, daily routines, and desirability of various system features. The survey was distributed through the following channels: Living at Home/Block Nurse Program, the Minnesota Senior Expo Conference, and personal contacts at Honeywell and the University of Minnesota. The final returned survey count was 54 (24 elder and 30 caregiver).

Early in the program, we identified the risk that caregivers may not know what they need or understand how technology might help them. A risk we did *not* identify was the problem of finding clients and caregivers who would respond to the survey. The reasons for this were many, not the least of which was the already heavy burden on their lives. The size of the survey (made larger by the use of large fonts) made it appear daunting and probably contributed to the reluctance to return completed surveys. Our best response came from individuals who were approached one-on-one by team members or others distributing surveys personally, rather than by mass-mailing.

Interviews: Interviews were completed with eight elder care specialists including Geriatricians, Geriatric Nurse Practitioners, and Pharmacists. The interviews revealed new opportunities for technology development and new user interface considerations. For example, specialists wanted to see 1) improvements in functional assessment, 2) remote observation of elder locomotion, 3) better coordination of medication information among elders, doctors and pharmacists, and 4) better coordination and communication tools to help doctors manage care with remote facilities/nurses. Special user interface considerations brought to light included sharing information with elders to make them an active part of the medical team and various means of interacting with individuals who have dementia so as not to introduce/exacerbate confusion.

Observations: Heartland Home Care allowed Honeywell team members to 'shadow' one of their home-care professionals on seven home care visits. The visits provided us a better understanding of the nature of interactions between formal caregivers and elders, the types of home environments and living arrangements I.L.S.A. must accommodate, and the processes and tools used by formal caregivers to manage the care they provide to their patients.

2.3 Emergent Functions Analysis

In traditional system development processes, many potentially valuable features and functions are overlooked because they pertain to interactions between the user and the environment, or possibly interactions between aspects of the environment, rather than specifically to interactions between the user and the system. To find as many of these potential features and functions as possible, we performed several analyses in which aspects of the environment were comprehensively paired off against each other or specific user disabilities and needs were comprehensively paired off against aspects of the environment. We documented any features or functions that each combination might imply.

For example, the interaction between certain cognitive disabilities and weather suggested the possibility that a client would leave the house in the middle of winter in Minnesota without putting on a jacket. This suggested a reminder feature that reasons about outdoor temperature when the client opens an outside door; if no closet activity is sensed, a reminder would be given to wear a jacket.

Together, these analyses produced 85 potential functions, including 38 conditions that should be alerted to caregivers, 10 functions based on special client needs and disabilities, and 37 functions that would provide direct assistance to the client.

Assistance Needs	Criteria				Average Score
	Prevalence in Source Material	Contribution to Institutionalization	Impact on Caregiving Resources	Limitation on Functionality	
Medical monitoring	9	9	9	9	9.0
Medication management	9	9	9	3	7.5
Mobility	9	3	9	9	7.5
Caregiver burnout	9	9	9	3	7.5
Dementia	9	9	3	3	6.0
Eating	9	3	9	3	6.0
Toileting	3	9	9	3	6.0
Safety	9	9	3	3	6.0
Isolation	9	3	1	9	5.5
Transportation	9	1	9	3	5.5
Housekeeping	3	1	9	1	3.5
Money management	9	1	3	1	3.5
Shopping	3	1	9	1	3.5
Wandering	1	9	3	1	3.5
Usability	3	3	3	3	3.0
Equipment use	1	1	3	3	2.0
Hallucinations	1	3	3	1	2.0
Alcohol use	1	1	1	3	1.5
Pressure sores	1	1	1	1	1.0

Table 1: Ranking of Assistance Needs (Scoring key. 1= low; 3=moderate; 9=high)

2.4 Selecting Features

Each opportunity identified above was discussed by the team, leading to a list of nearly 300 technology opportunities of interest to elders, their caregivers (formal or informal), and other interested parties (e.g. insurance). Opportunities were classified into general categories such as communications, activity monitoring, user monitoring, environment monitoring, reasoning, memory support, workload support, social support, event detection, and others.

We conducted a series of Six Sigma (6σ) analyses to narrow the technology opportunities list to an achievable feature set of approximately 20 items. To do this, we created a Decision Matrix to determine the importance factor associated with each assistance need (Table 1). Importance was based on prevalence, contribution to institutionalization, impact on caregiving resources, and limitations on elder functional ability.

We associated technology opportunities with assistance needs, then dropped those of low priority—75 technology opportunities remained. Through several other 6σ tools, we made a conscious decision to focus on needs related to daily living rather than medical concerns. Second, technology for medical monitoring is well advanced already, with numerous products already on the market. We preferred to focus on the more risky technology of monitoring daily activities of the elder. We also preferred items that could be be implemented in one year and a few high impact items which could be done in two years.

To achieve the final list of 22 features, we determined the minimum number of technology opportunities that, when taken together, would satisfy an assistance need. The final list was designed to satisfy needs for:

- Medication management: verify medication taken.
- Toileting: monitor activity, provide path lighting.
- Mobility: measure activity level, detect home and away, detect falls.

- Safety: monitor environment, panic button, intrusion detection.
- Usability: no password for client, queries to elder, operational modes (sick, vacation, guest), feature controls (on/off).
- Reporting: alarms, alerts, notifications, reduced false alarms, reports by phone and Web.
- Caregiver burnout: to-do lists, reminders, remote access, coordinate multiple caregivers.

3 System Description

3.1 Architecture

During the requirements analysis phase of I.L.S.A. development it became apparent that installations would (1) be in homes with unique layouts and suites of sensors and actuator capabilities and (2) support technophobic clients with differing abilities, needs, and care-giving support networks. Because clients age [52], and technology changes, I.L.S.A. had to be rapidly deployable, easy to configure, and easy to update. It needed to facilitate the evolution of any installation by providing an open architecture into which new devices and reasoning modules could be plugged.

To meet these requirements, we decided to use an agent-oriented approach [38]. An agent-based architecture would provide modularity, distribution, functional decoupling, and dynamic discovery of capability as well as a publicly available ontology.

Agents are responsible for components essential to good system performance at several levels of computational responsibility, from device control to client task tracking. We defined an I.L.S.A. agent as a software module that (1) fulfills a single task or goal and (2) provides at least one agent interface. Agent interfaces provide the inter-agent communication and interaction. In contrast to the task-organized functionality provided by agents, the agent interfaces allow the agents to provide functionality to each other.

To facilitate description of functionality, there are four main categories of capability that fit into a layered hierarchy as shown in Figure 2. Layers provide a framework in which to describe an agent's capability, rather than a strict enforcement of code. We selected JADE as the basis for the agent communication layer [7].

The agents in the system included device controllers, domain agents, response planners, and system management. One of each of the following agents were created for each human client:

- **Medication**: monitor use of medication caddy, raise alerts and generate reminders.
- **Mobility**: calculate statistics about the elder's mobility, raise alerts.
- **Modes**: monitor client selection of on/off status.
- **Reminders**: schedule and initiate reminders as specified by caregivers.
- **ResponseCoordinator**: suppress and merge alerts and reminders as appropriate; see [93] for more details.
- **Machine Learning**: record alerts for unexpected activity based on profiles of normal behavior (users did not see these alerts).

Figure 3 sketches the Mobility agent: its inputs, decisions, and outputs.
Exactly one each of the following agents was created on the server (one server for all the human clients):

- **PhoneAgent**: format messages for presentation and manage communication with appropriate contactee(s).
- **Platform**: provide general services, e.g. normalized time, for all agents in the system.
- **Databases**: control access to client data and ensure database consistency.

In the research system, we explored task tracking (Section 9.1), several different machine learning techniques (Section 9.3) and several more domain agents.

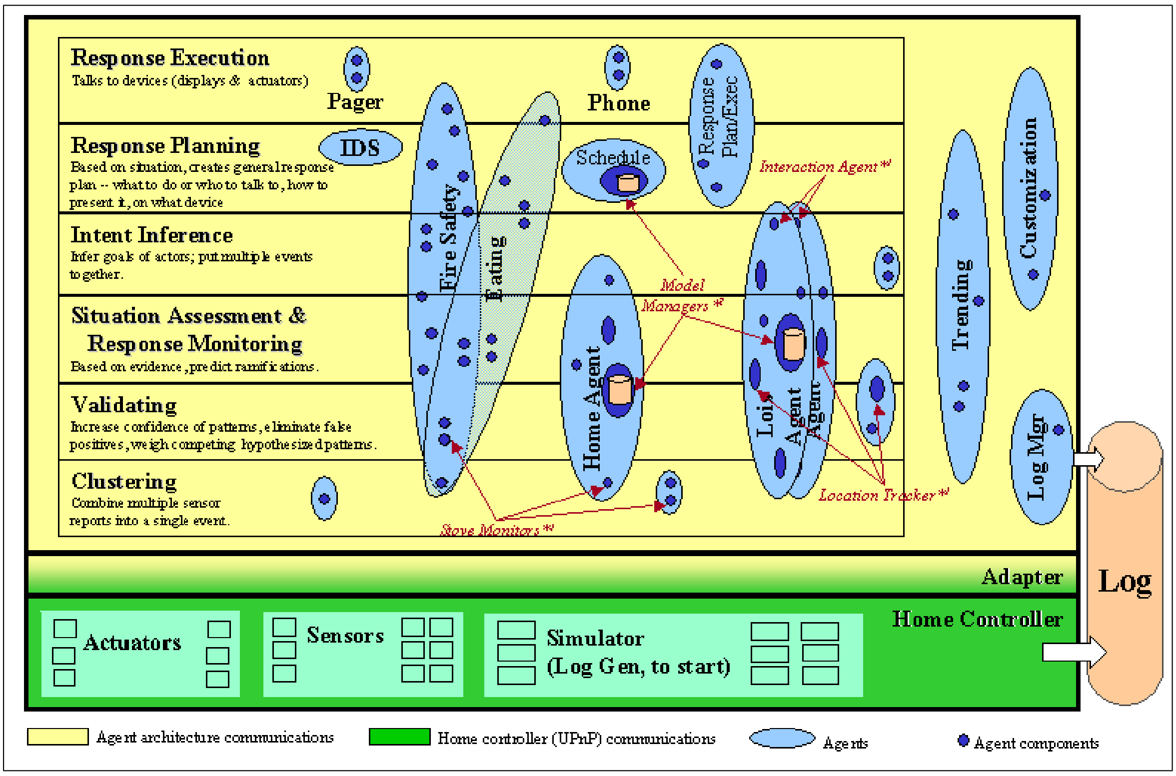

Figure 2: I.L.S.A.'s agent-based concept.

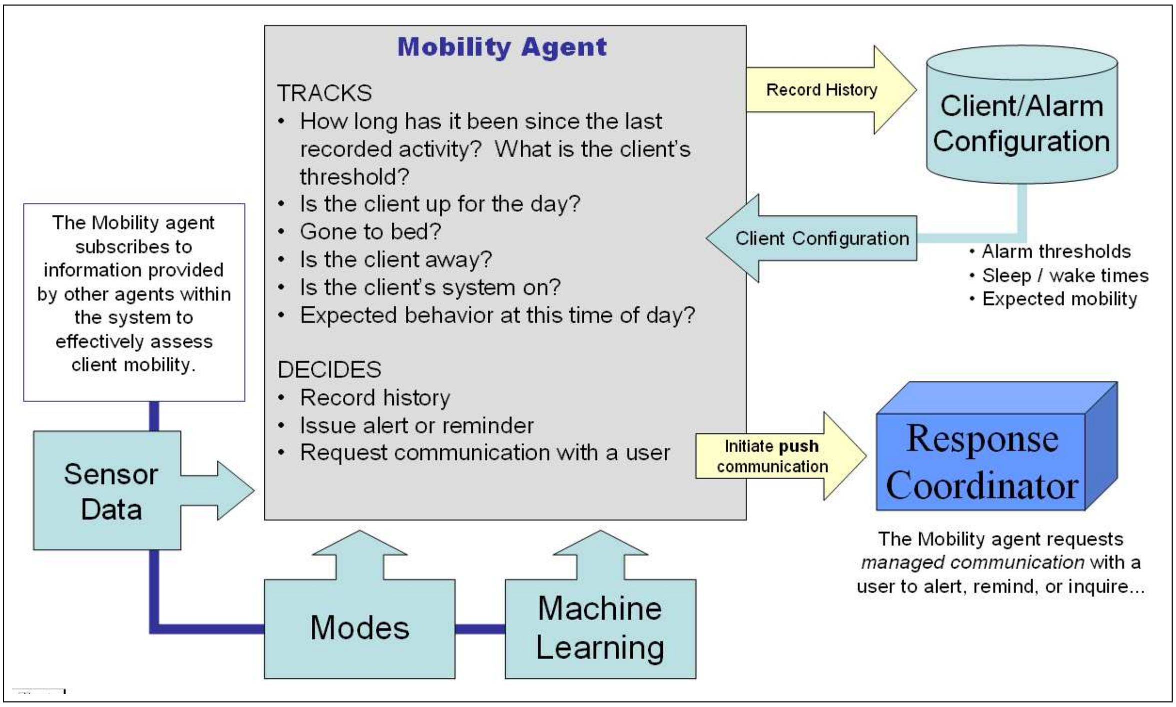

Figure 3: The Mobility agent tracks the client's activity.

The hardware employed in the I.L.S.A. field test consisted of readily available Honeywell home automation and control products. The Honeywell Home Controller served as the backbone for communicating sensor events out of the home. Events from standard Honeywell security sensors were packaged as simple XML strings for transmission to the Honeywell Global Home Server™. I.L.S.A. was designed to operate on real-time data from the home, so reliable broadband access was a crucial linchpin of this architecture. Figure 4 shows a high-level sketch of I.L.S.A.'s data

House Number	Number of Occupants	Number of Sensors	Type of home	Number of Days of Data
Engineer 1	1 adult, 1 80-lb dog	16	Own	62
Engineer 2	2 adults	20	Own	40
Engineer 3	2 adults	10	Own	81
Engineer 4	1 adult	10	Own	34
Client 1	1 adult	4 motion, 1 med	Apartment	180
Client 2	1 adult	4 motion	Assisted	183
Client 3	1 adult	4 motion, 1 med	Apartment	149
Client 4	1 adult	3+ motion, 1 med	Apartment	142
Client 5	1 adult	4 motion, 1 med	Apartment	149
Client 6	1 adult	5 motion, 1 med, door, mat	Apartment	146
Client 7	1 adult	4 motion, 1 med, door, mat	Apartment	107
Client 8	1 adult	4 motion sensors	Own	102
Client 9	1 adult	5 motion, 1 med	Own	164
Client 10	1 adult	8 motion sensors	Own	119
Client 11	1 adult	5 motion sensors, 1 med	Own	124

Table 2: Sensor installations for the 15 homes in the I.L.S.A. tests.

collection and communication backbone.

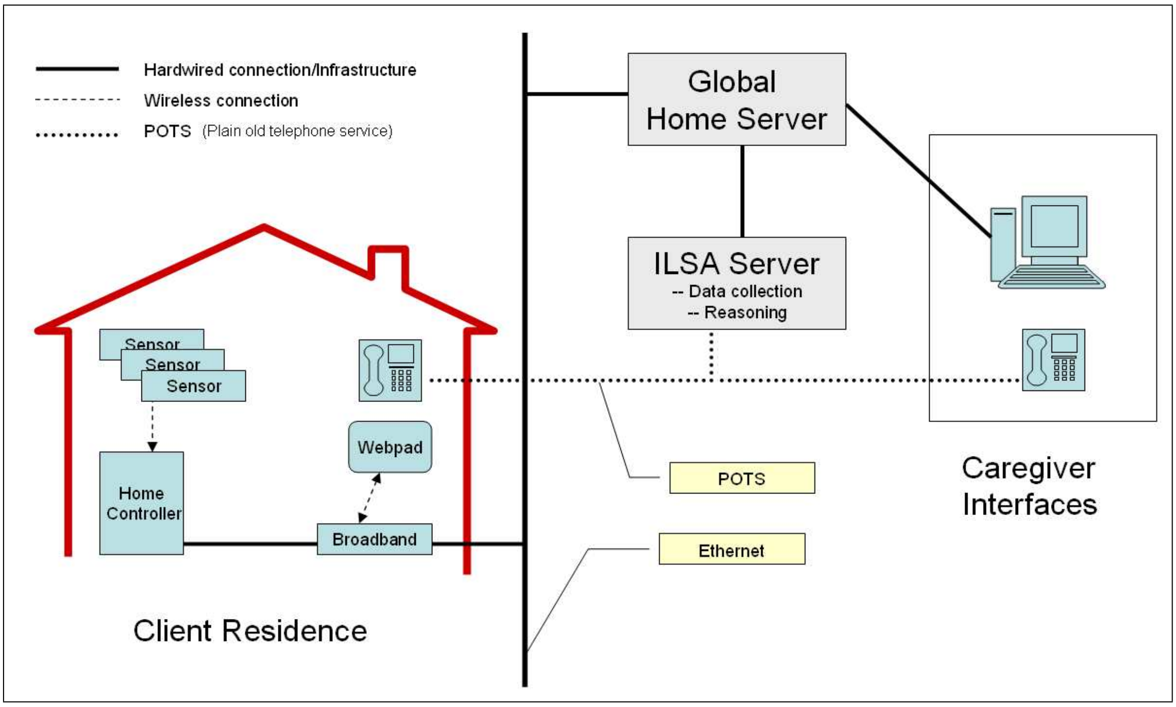

Figure 4: High-level view of I.L.S.A. hardware architecture.

3.2 Field Study Environments

We installed I.L.S.A. in the homes of four system engineers, and eleven elderly clients. Table 2 summarizes the homes.

From July 2001 through December 2001 we focussed on hardware configuration, determining which sensors were most effective. During this phase, we installed systems in the homes of four engineers and collected real-time sensor data. Employees kept corresponding logs to enable us to verify our ability to identify activities based on sensor events. Each of these installations had between 10 and 20 sensors, including motion sensors in every room, door contact switches on all exit doors, medication caddies, pressure mats in 'strategic' locations such as the bathroom sink, flush sensors, a medication caddy, and security sensors. No reasoning components or user interfaces were included in these deployments.

Beginning January 2003, we installed I.L.S.A. into the homes of eleven elders and collected data through July 2003. Seven subjects lived in apartment units in two living facilities in the St. Paul area, and four subjects lived in their own homes in Florida. We limited the number of sensors in the elders' homes for reasons of cost and concerns about privacy—for example, it would have been difficult to find appropriate test subjects who would accept a system with a toilet flush sensor. Each test home had from four to seven sensors, including one medication caddy and several motion detectors. Two installations had a contact switch and pressure mat at the exit door.

3.3 Field Test Features

The main goal of the field test was to demonstrate the complete cycle of I.L.S.A. interactions: from sensors to data transmission to reasoning to alerts and home control. The field study was also designed to determine the effectiveness of this type of product in maintaining or improving the independence of the elderly subjects.

As described in Section 2, we selected our initial feature set based on their importance ranking, the ability to exercise the full range of technical capabilities of the I.L.S.A. architecture, and the need to learn more about a particular area. The ability to implement and appropriately support a robust test application was the final determining factor. The system we field tested had the following significant features:

- Passive Monitoring: basic mobility, occupancy, medication compliance, sleeping patterns.
- Cognitive Support: reminders, date/time of day.
- Alerts and Notifications: auto contacting caregivers (by telephone).
- Reports: summary reports of client behavior.
- Remote access to information via the Internet or telephone (allowing users to monitor or interact with the system).
- Control: modes (on/off).

Other capabilities and features were tested in the lab.

3.4 User Interface

We considered a range of interface options for delivering I.L.S.A. features to clients and caregivers, including the Web, telephones, pagers, PDAs, speakers and microphones, electronic picture frames, and television remote controls. We selected the Web and the telephone.

Elderly clients were equipped with Honeywell Web Pads™ with wireless access to the Internet over a broadband connection. Through the Web interface, the elders could display:

- Reminders: Display of reminders issued for the day.
- Medication status: Medication schedule and status (taken/not taken).
- Mobility status: Mobility summary.
- Controls: client control over alarm delivery (on/off).
- Caregiver information: List of people with access to their data, and messages issued recently.

Figure 5 shows a sample web page for the elderly client. I.L.S.A. could also deliver reminders to the elder by telephone.

Caregivers could access I.L.S.A. data about their client/family member with their normal ISP Web connection. The caregiver Web interface included these features:

Figure 5: A sample webpage from the elder user interface.

- Notices: View and acknowledge alerts.
- Status: View general ADL status (including historical trends for medication and mobility.
- Profile: View and edit. prescription and medication schedule.
- Configure: Set up scheduled reminders and personalized activity alerts.

Alerts and reminders could be delivered by telephone. In addition, a dial-in telephone interface allowed caregivers to get abbreviated status reports and record and schedule reminders for the elder.

3.5 Client Selection and Testing

The field test was designed as a prospective cohort study of six months. I.L.S.A. was installed in client homes at the start of the field test, and monitored clients continuously for the six month period. The study protocols were approved to the Institutional Review Boards of the University of Minnesota and of the National Institutes of Health.

Demographics: The Minnesota sample included six women and one man, ranging in age from 76 to 96 years. The eldest client resided in an assisted living apartment while the others lived in independent apartments. The Florida clients, who were all in their own homes, consisted of three women and one man, ranging in age from 55 to 76.

Measures: Client daily routines were assessed by questionnaire; we asked about medical history, medications that were prescribed, daily times for getting up, taking meds, performing routine activities, mealtimes and bedtimes. (See Section 6.2 for a description of how this supported configuration.) We also determined their level of comfort with technology.

Caregiver participation in the life of the client was assessed by questionnaire using the Montgomery Caregiver Burden Scale. We also assessed their level of comfort with technology.

Usability was assessed via weekly and monthly phone interviews of clients. Caregivers were asked to complete these questionnaires on the web or to mail them in. In addition, two focus group sessions were scheduled to gain insight about the clients' experiences with I.L.S.A.

Health of clients was measured by responses to questions on the Short Form (SF-36) of the Medical Outcomes Study at baseline, midpoint and conclusion of the field test. Cognitive ability was measured by scores on the Mini Mental Status Exam (MMSE). At three months into the study and again at its conclusion, Dr. Krichbaum administered the SF-36 and the MMSE to clients. At these same data points, focus group sessions were held to which all clients and caregivers were invited.

Note: There was considerable risk in the selection of individuals for this test. To test appropriately frail elders may put them at risk if they do not place appropriate levels of trust in our prototype. To test elders that are not frail enough may not produce accurate data about usefulness of features. To some degree I.L.S.A. suffered the effects of these risks throughout the study as noted in Section 12.

4 Lessons Learned

Each stage of I.L.S.A. development and deployment provided learning opportunities. Many of these represent risks we uncovered during execution of our plan. Some of these inspired innovation in design, and others were outside the scope of what we were able to implement during the program and represent opportunities for future development. Significant issues we encountered (discussed in detail below) fell into these categories:

- Collecting data from third-party devices
- Configuring the system
- Agents
- Developing and making use of an ontology
- Automated Reasoning
- Designing and deploying usable interfaces
- Client selection and testing
- System Integration

While this paper focusses on the technology and development issues, we noted several barriers to the commercial deployment of an I.L.S.A.-like system. Those barriers include ease of installation and maintenance, development of adequate installation and monitoring services, successful integration with third-party providers, and accurate sensing of significant events in the home.

5 Lessons: Data Collection

Part of the I.L.S.A. program involved exploring which sensor data might prove useful for understanding clients' well being, activity level, and need for support. As discussed above in Section 3.3, we based our final sensor selection and installation on the data features that were important to our audience and our ability to implement them well.

Notable issues in this area concerned:

- Sensor selection
- Sensor placement
- Data transmission methods

5.1 Lesson #1: Sensor Selection

As this project did not entail new sensor development, we generally used off-the-shelf sensor solutions. Most of these sensors were designed for security systems and give only discrete states of open/closed, or presence of motion or pressure—they give no real information about the signal source.

Before our final decision to implement only in-home motion and medication monitoring solutions, we explored ideas for collecting a broader set of data. (The sensors we actually used are discussed earlier in Section 3.2.) Areas of special interest included identifying actors in a multi-client environment, discovering whether a client had fallen, discovering whether the client had performed a specific activity (eating, leaving the house, sleeping), and receiving and responding to panic/emergency alarms.

We found that:

- Video identification is complex, expensive, and generally perceived as an invasion of privacy.
- Identity tags are expensive and clients may forget to wear them.
- Pressure pads present a trip hazard, are easily damaged and expensive to install.
- Motion sensors are inexpensive and easy to install, but difficult to place for reliable information about client location.
- Photoelectric beams are highly accurate but expensive.
- Clients are reluctant to use worn sensors such as panic buttons and fall sensors.
- Clients are more likely to use the simpler medication caddies.

For many monitoring needs, we can rarely determine the true state. For example, we can only monitor whether the medication caddy was opened, or whether pills were removed from their containers, *not* whether the elder ingested the medication. Similarly, we can only determine whether the elder is in bed, *not* whether s/he is actually sleeping. In general, this kind of *related* information is enough for a caregiver, but the caregiver needs to be very clearly told the limitations of the system, and any user interfaces must use accurate and unambiguous language to describe that data. The risk is that a caregiver will come to rely on the system for more information than it is designed to provide.

The following paragraphs give more detail about sensor selection for each of several monitoring needs. Section 6.1 gives a description of the issues we encountered in configuring the hardware.

Client identification: We investigated several methods for determining which client in a multi-client home was actually performing an action, including worn location identifiers and video identification. During experiments with client identification using digital image processing of video signals, we quickly realized this approach would not be appropriate for I.L.S.A.'s needs: too much technology would need to be developed and clients still have strong concerns about privacy.

We learned that worn identifiers, which could be coupled with fall sensors, have two disadvantages: (1) they are cost-prohibitive for most independent elders, and (2) since they are body-worn, the elder may forget (or choose not) to wear them.

After investigating these approaches, we decided to mitigate the risk of inaccurate identification and invalid data by concentrating on single-client households for our current project.

Future Needs: Presently, privacy and affordability are barriers to the use of many promising technologies. As privacy concerns change and technologies mature, the use of cameras or other more sophisticated tracking systems may make multi-occupant activity monitoring more feasible.

Mobility: Measuring mobility includes determining the client's level of activity, movement from room to room, and other related measures. Current technology offers several types of sensors that are useful for measuring mobility, including motion sensors, contact switches, photoelectric beams, and pressure pads.

For the field test, we chose to use motion sensors to determine amount of activity. Motion sensors need to be very carefully located to ensure accurate measurements (see Section 5.2).

Pressure pads have attached contact closures and are taped to the floor or positioned under a carpet in a useful location (by a bed, in a door entry, etc). The contact records when someone has walked across the pad. We found these to be nearly unusable in a home setting because clients might leave heavy objects on them, stand on them (the sensor would fire constantly), or otherwise move and damage the contacts. Installing pressure pads in a way that ensured they could not easily be moved, damaged, or present a trip hazard was expensive, making them inappropriate for most of our uses.

Photoelectric beams reliably indicate when a person walks through/into a specific space. They are much more accurate than motion sensors, but are costly to install. A particularly good use we found for these sensors was to install them at the top and bottom of stairwells to determine whether an occupant has moved up and down the stairs.

Occupancy (Home/Away): Determining whether a client is actually at home or not can present problems; a single passive sensor is unable to do so, but a group of sensors can be a fairly reliable determiner of occupancy. We found that a combination of a contact switch on the exit door, a pressure pad outside the door, and a lack-of-motion inside the home to be a reasonable measure, but does not guarantee 100% accuracy.

We also tried requiring clients to pro-actively turn I.L.S.A. off when they left. Clients were reluctant to do so because they were afraid they'd forget to turn the system on again. One possible solution would be to detect the client's return and intelligently prompt her to reactivate the system.

In two locations we used a contact switch and pressure pad on the exit door to detect whether the client may have exited. Using this method we were able to filter more than 90% of "no-motion" alerts that occurred when the client forgot to indicate that he/she was away from the apartment.

To report accurate and useful information about mobility using motion sensors, particularly lack-of-mobility, a reliable *passive* occupancy detection system must be developed. Ideally, the occupancy solution could also address the identification problem noted earlier.

Sleeping: We used reports from motion sensors to indicate whether the client was getting up at night. Unfortunately, most of the motion sensors were too sensitive, and we had to essentially ignore the bedroom motion sensor completely; we determined "sleep" based on the *in*activity of sensors outside the bedroom.

We did not explore other approaches for determining night-time activities, such as weight sensors on the bed.

Medication: Medication can be dispensed from a dedicated caddy with contact closures that indicate whether the caddy was open or closed. We found some tradeoff between simplicity of use and accurately determining which medication container was opened.

We considered several approaches and evaluated commercial offerings, including automated pill dispensers and caddies that determine which medications are accessed. Our interviews with health care professionals, however, indicated that automated pill dispensers are complex and highly prone to problems. Moreover, they informed us that detailed reports of "which medicine" and "how much" were more than what was strictly necessary in most cases. (In the field test, some caregivers expressed a desire to know more about the specific medications taken, but it is not clear that more elaborate solutions really address that with any higher level of assurance.)

We therefore proposed an approach to simply determine access to the entire set of medicines, thereby capturing the important information about whether a client has remembered medication at an appropriate time of day.

We constructed prototypes for our test sites that held existing pillboxes inside instrumented containers. Our simple one-sensor medication caddy (shown in Figure 6) was effective in sensing the medication habits of our clients and in reminding them of missed medication events. Elders disliked the reminders so much that they became more compliant with their medication schedules in order to avoid receiving the reminder (the reminder was only generated if the elder had not taken their medication). By encouraging them to exercise their own memory in this way, the solution appears to be non-addictive—that is, the incidence of missed medications did not seem to increase when the reminders were discontinued. Figure 7 shows that most test subjects showed a reduction of missed medication events over the course of the study.

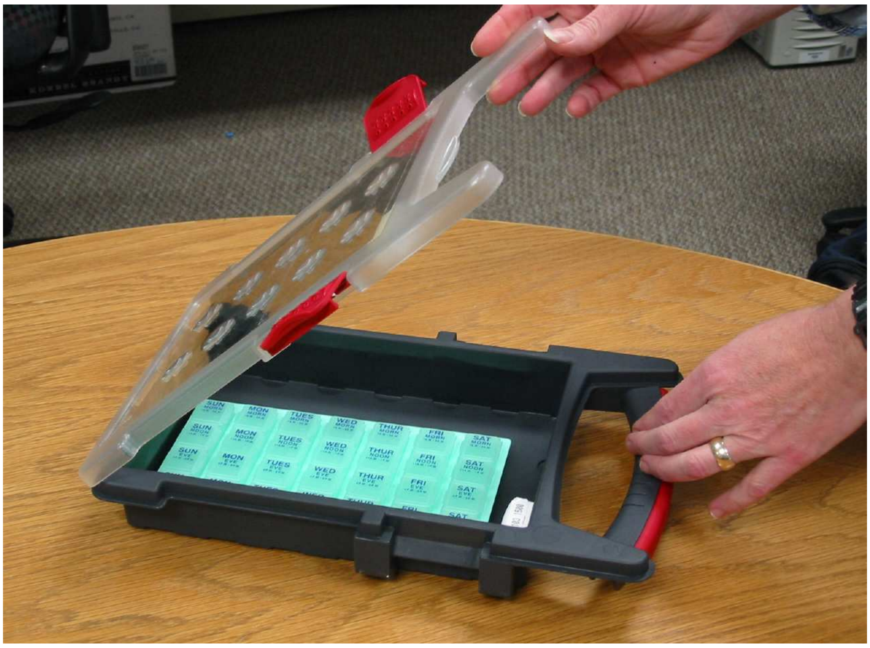

Figure 6: One version of the simple one-sensor medication caddy used in the field study.

Another point in favor of the simplified approach was that the test subjects could continue to use their preferred method of medication storage/organization. Most subjects used a common weekly pill sorter placed inside our sensored container. Some of them require caddies in more than one location to support their current habits (kitchen, bedside), and the I.L.S.A. solution supports that easily as well. Many of our female participants commented that the appearance of the box made a difference in their acceptance. This solution supports the use of any dedicated space as the container.

To summarize, our medication compliance approach provides the following improvements over the competition in this area:

- little disruption from current habits
- no additional interaction with the system outside normal medication handling
- reduced intrusion by unnecessary reminders
- continued exercise of the client's remaining cognitive faculties (i.e., incentive to remember

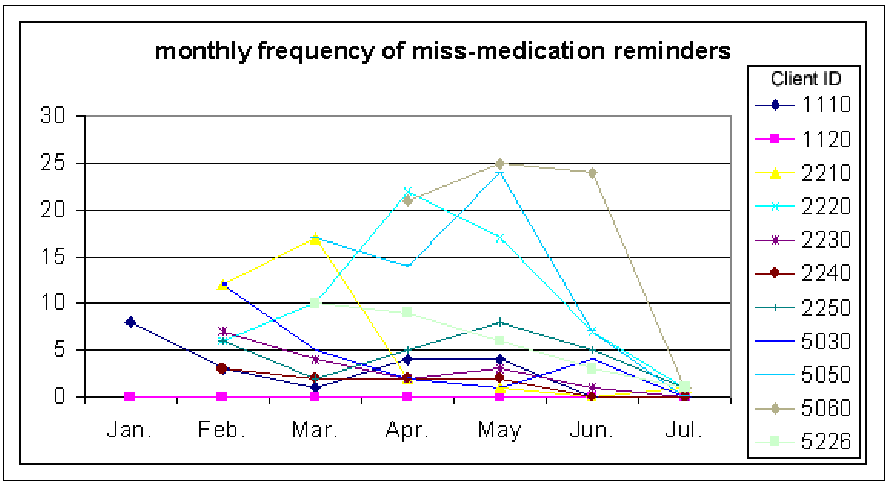

Figure 7: The incidence of missed medications declines over the course of the field study.

on their own)
- no complex or strange-looking devices to cause discomfort or confusion

Further Needs: No medication caddy, regardless of the sophistication, can tell you when a person is"tricking" the system. Systems such as these only work for individuals who are interested in being compliant. They can not assure you that the person *ingested* the medication in question. If a guarantee is required, a chemical-analysis toilet should be considered (see toileting).

Panic button: Since we were unable to provide 24-hour coverage of panic incidences during this test, we did not implement a panic button system. (Note that removing this feature does not in any way reflect on its priority with elders and caregivers.)

To provide the elders with an appropriate level of confidence and security, we provided them with a commercial emergency response system if they did not already have one. Initially we had hoped to collect the alarm data from these systems for use by I.L.S.A., but the level of access that we require was not available from those third-party systems. To our knowledge, the only subject to use the emergency service during the test period was the one in assisted living (one incident).

Though we did not implement our own version, we learned through interacting with our clients that they are extremely averse to wearing panic buttons, so much so that even the very frail frequently refuse to carry them consistently. The main reason for this reluctance is that the sensors *look* like sensors, hence making it obvious to observers that the elder is being monitored; a sensor that looks like jewelry, for example, would be much more acceptable.

It is our assessment that the need to deliver peace-of-mind for both the client and their caregiver(s) cannot be served without 24x7 professional monitoring. Activity monitoring by informal caregivers alone does not deliver the same level of assurance of response. No system, no matter how robust, can reach someone who is not at the right location, or whose cell phone is turned off or out of power.

Falls: Dedicated fall sensors must be body-worn, but are effective and becoming more reliable (fewer false positives). We brought in prototypes of several commercial-off-the-shelf (COTS) offerings. Doughty [25] provides an excellent review of fall sensing technology for older adults. Our limited experiments with these sensors indicate that those employing accelerometers are more accurate, provide more data, and are far less prone to false alarms than those that sense orientation (vertical vs. horizontal).

Despite an extreme fear of falling, as with panic buttons, elders are resistant to wearing a device that advertises frailty. Elders seem more accepting of wearing a fall sensor than they are of wearing the panic button, possibly explained by the fact that elders are most worried about situations where the panic button would be useless (i.e., unconsciousness).

We explored several passive (non-video) techniques for detecting falls, including seismic sensors and photoelectric beams in key locations (e.g. stairwells). Seismic sensors were much too sensitive and unable to distinguish falls from other "bumps". Photoelectric beams were unable to determine whether the client turned around, stood in one photoelectric beam, or moved back and forth across it as they decided what to do.

Further Needs: None of the fall sensors presently on the market are 100% effective at sensing a"crumpling" body. Elderly people frequently fall in graceful ways, catching themselves on nearby objects, slumping against a wall, or otherwise falling or landing in positions that would not set off alarms in any of these sensors. It may be that other body-worn biometric devices, possibly enabled by nanotechnology, may provide a more reliable alternative by sensing changes in pulse, blood pressure or respiration.

Eating: One area we considered for monitoring was whether a client was eating regularly. An appropriate sensor suite would be a combination of sensors on cupboards and appliances, and motion sensors in the kitchen and dining rooms. The difficulty here is that the only real information the sensors can give is presence or lack of activity in the kitchen, not whether someone is *actually* eating. No matter how reliable the sensor data is, lack of activity doesn't mean the elder did not eat (e.g. a meal may have been brought in), and activity does not mean the person is actually eating.

Toileting: Toileting can be an indicator of health, and we experimented with a several approaches to gathering data. The extreme approach is a Toto™-style toilet, which analyses urine for glucose, protein and blood, registers weight, blood pressure and other information.

The simple approach we tried was to detect motion in the bathroom, and couple it with a toilet flush sensor. We also tried enhancing it with tightly directed motion near the toilet. However, none these simpler approaches can distinguish toileting activity from cleaning the toilet, for example.

Notably, based on our user studies, even the simpler approaches are unlikely to be acceptable for the near term future. As none of the clients we worked with were incontinent, we did not explore these privacy issues in more detail.

Our analysis showed that the chemical toilet could potentially be the most effective sensor in the home—it monitors health conditions, medication compliance, eating, as well as basic mobility, and moreover does not suffer from being unable to disambiguate multiple users.

5.2 Lesson #2: Sensor Placement

We discovered very early that sensor placement is much more critical than we had anticipated. For example, a sensor incorrectly placed to see kitchen activity may have a line-of-sight that leads into a hall or another room. If the reasoning software triggered a call to a caregiver based on lack of kitchen activity, no call would be made if the client walked through the hall but never entered the kitchen. Bedroom motion sensors were often activated by normal nighttime motion (e.g. turning over in bed), and therefore were ineffective at detecting "up-at-night". Moreover, sensors aimed too low toward the floor could actually work against the intent of the no-mobility alert by picking up flailing arms or legs associated with a person in distress on the floor.

These problems can be alleviated with careful sensor placement and/or collaboration of inputs from multiple sensors.

Sensor accuracy is not measured only by the quality of the sensor, but also the sensor placement and hence the quality of the installer. This sensitivity increases the cost of deployment by requiring more skilled installers.

5.3 Lesson #3: Data Collection & Transmission

Sensors designed for security systems are not well-suited for a continuous monitoring environment. For example, door sensors raise alarms when the door is opened, and *continue raising the alarm until the door is closed or the security system is turned off.* In a continuous monitoring environment, however, a door may be opened for air circulation; the sensor starts "shouting" and drowns out the signals of other sensors. A more appropriate sensor design would be to report only the change-of-state. Motion sensors meanwhile, merely indicate the presence of motion, without indicating how much motion, the size of the object, or its location.

We tested the system using a broadband connection so I.L.S.A. could react to sensor data as it occurred. Real time reaction (meaning within a useful latency) is important, but it can cause problems if the broadband connection goes down at a critical time. In dealing with life-critical situations, we need exceptional reliability and recovery features. The I.L.S.A. test system suffered from a lack of several failsafes that would be essential in a commercial monitoring system:

- System and sensor connectivity/health monitoring.
- POTS (plain old telephone service) backup for broadband connectivity and debugging.
- Persistence and recovery protocols for agents in the system to make system reboots less disruptive to monitoring.

6 Lessons: Configuration and Customization

Configuring, installing, and customizing I.L.S.A. for each client consisted of (1) installing or delivering the necessary Internet service, sensors, controls, and Web Pads to the clients' homes and (2) entering client-specific data into centralized databases. Over the course of configuring 15 homes, we learned a good deal about our specific design and some lessons that are applicable to any similar, multi-client system.

- Hardware installation is never easy. Each home was a new test of the sensors, the communications, and the installer's nerves.
- Request only the client data you expect to use.
- Base configuration on objective data wherever possible.
- When subjective information is required, make sure that the instructions coincide with the implementation and, if possible, re-configure when objective data is available.

Elsewhere in this document, we present issues generic to the I.L.S.A. system. In this section, we discuss issues related to making I.L.S.A. available to individual clients.

6.1 Lesson #1: Hardware Configuration

Even though the data collection architecture was tested in engineer's homes early in the program, deployment to client sites proved problematic. Small changes in network configurations, differences in broadband service providers, wireless networking issues and numerous other issues, including faulty or inadequate hardware components conspired to make each installation a unique experience. Even within the same community living facility, using the same broadband provider, small differences in wireless configurations caused significant consternation in one or two units. Correct configuration was never straightforward.

In part, these issues were related to the use of off-the-shelf components that were not originally designed for this usage scenario. The evolution of Internet security practices, messaging protocols, and everyday service reliability issues also came into play. Finally, the complexity of this system, the novel use of the components, and the limited (and distributed sites) made it impossible to build a sufficient installation experience base.

Every test site selected was eventually brought successfully on line, though many required several hours of active debugging, multiple visits, and special instrumentation to track down root causes. Once on-line, all but one of the test sites remained on-line for the duration of the test, except during Internet service outages.

Though the architecture choices were appropriate for our purposes, the following issues should be accounted for in a product architecture:

- Broadband service availability, reliability and troubleshooting.
- Installation standardization.
- Hardware simplification/standardization.
- Tools for testing/verification of installation.
- In-depth training for installers.

6.2 Lesson #2: Collecting Configuration Information

Deploying I.L.S.A. in a home requires information about clients and caregivers, including contact information, capabilities, medications, and living habits. We asked caregivers to complete forms, and had a field worker (in our case, researchers or nurses) interview the client.

The form describing medication regime requested medication names, reason for using, schedules for taking, dosage type and size, and prescribing physician. The format worked well and translated easily to the data base and interface design and usage. It succeeded because the information was wholly objective.

On the other hand, the form for obtaining mobility data was both subjective and poorly matched to our data collection design. Here we asked clients to assess how active they were during each day-period (morning, afternoon, evening, night) on a 7-point scale.

First, the 7-point scale was misinterpreted. The questionnaire instructions told the client to consider housework as 5-7 and sleeping as 1. What we *really* wanted to know is "do you move around a lot?" *not* "how hard do you work?" Furthermore, we found that users who said they are very active at night are speaking relative to what they *think* they should be doing—so selecting a 5 or 6 for night time activity means something different from the same selection during waking hours.

Second, I.L.S.A. expected the degree of activity to be measured over the entire 6 hour day-period. That is, I.L.S.A. considers a client "extremely" active if s/he triggers the detectors at least once every 15 minutes for six hours. Even if the client does calisthenics for half an hour, and then leaves the house for the remaining five and a half hours, I.L.S.A. would consider him to be only "1" active (two 15-minute periods in 6 hours).

As could be expected, the mobility ranges we configured seldom agreed with the clients' actual mobility. For the most part we found that they overstated their activity levels, so the mobility comparisons were generally low.

Several other domain agents (tested in the lab and not released in the field study) required configuration information including specific routines and behaviours. For example, to track whether the client is eating, the *Eating* agent needs to understand which sensors directly relate to eating, the times that correspond to eating activity, and what information is irrelevant (e.g. walking through kitchen to get to back door). We explored *task tracking* capabilities [32] to monitor activity and detect when clients were trying to achieve particular goals, but there are two significant obstacles: (1) the sensor suite needs to be quite rich, and (2) it is hard to configure models of behavior that are general enough to cover all activity. (See Section 9.1 for more detail.)

We see two solutions to these problems: (1) design a questionnaire that is completely objective and asks for *exactly* the right information, and (2) utilize Machine Learning techniques to automatically configure the information based on collected data; see Section 9.3.

A significant risk for this kind of monitoring system is that clients and caregivers may simply be unable to provide objective information about activity and living patterns, even if the questions are completely objective. We have shown that machine learning techniques can be successfully applied to reduce the risk of inaccurate configuration based on interview alone. Unfortunately, machine learning algorithms still require several weeks worth of data to be effective in supplying information about actual patterns. While systems that use this approach will be far more reliable in the field, they will require a "getting to know you" probationary period during which special handling of notifications should be expected.

7 Lessons: Agents

In addition to meeting I.L.S.A. requirements, we expected that the agent-based approach would provide the following benefits [38]:

Distributed Development. Because an individual I.L.S.A. agent is intended to perform a single task, development of each agent could be assigned to a separate software engineer who could work independently.

Reusability. The agent is the basic delivery and compositional unit of I.L.S.A architecture. We expected to be able to easily add or replace agents as the need for new functionality arose.

Robustness and Reliability. A key aspect of multi-agent systems (MAS) is distributed processing and control. In theory, this architecture means that multi-agent systems will not crash with a local single point of failure.

Scalability. Because of the complexity and number of problems it needs to address, a full-scale monitoring system for multiple clients requires functionality that is not computationally feasible in a centralized system. We expected that the distributed architecture would support a much more scalable system.

Agent-based approaches to system development are still relatively new. Robust infrastructures for applying this technology to a real-world system are not commercially available; research prototypes are not yet fully reliable and are mostly unsupported. There was considerable risk in basing the I.L.S.A. field test on this cutting-edge infrastructure. Further details of those risks are provided in the remainder of this section.

I.L.S.A. was one of the first agent-based systems seen by "real" people outside the lab. As a result, we identified several risks and pitfalls in developing agent-based systems that had not been previously identified. We also describe new ways to address and mitigate these risks.

7.1 Lesson #1: Distributed Development

Since each I.L.S.A. agent performs a single role, we anticipated rapid deployment of the system facilitated by assigning development of each agent to a separate software engineer. However, even during the design stage it became apparent that agents could not be developed independently of each other. Even though each agent is responsible for a single task, these tasks are interrelated with those of other agents. For example, when a *Medication* domain agent generates a reminder to take a medication, it is processed by the *ResponseCoordinator,* which coordinates interactions over multiple domain agents. It is then delivered to the client by the *Phone* agent. All three agents share a single goal—delivering a medication reminder to elder—and must be able communicate with each other. We believe that the development issues we had to face are not specific to I.L.S.A. but are general to agent-based systems, where agents work cooperatively toward achieving a common goal.

To support inter-agent communication, the development team needed to resolve such issues as communication protocols, recovery from failures or exceptions in agent conversations, and ontology development for semantic information exchange. Resolving these issues required a good deal of coordination among team members and added considerable overhead to development time.

The need for agents to communicate and work together to achieve a common goal also resulted in complications during integration and debugging. We found there was inadequate support to localize bugs. An error generated by an agent does not necessarily identify the root cause of the problem. Errors can propagate from agent to agent through communication channels, making it difficult to identify the agent at fault.

7.2 Lesson #2: Reusability

When we chose an agent-oriented approach, we expected to use a small set of agents to provide basic functionality for each installation of I.L.S.A. Each installation could be further customized by adding specialized agents. As client requirements or technology capabilities evolved, agents could be replaced with different versions. Choosing agents according to functionality would allow the client to customize the system to deliver specific functions. The client would then only pay for what they need.

We also did not expect the degree to which developing new capabilities would require complete re-development of the system. We did not recognize that adding new agents would require developing new functionalities and interfaces in existing agents. Thus, every time an agent is added, thorough testing of the entire system is needed to check for behavioral and data coherence issues. While these kinds of issues arise in all agent-based systems, they are more severe in a tightly-coupled agent system like I.L.S.A.

7.3 Lesson #3: Scalability

One project goal was to design a system able to handle a large number of clients. Agent technology currently does not address scalability issues in any meaningful way. To build a scalable system we had discover how to properly scope each agent. On one hand we wanted to build lightweight agents, but on the other hand we wanted to keep agent coordination and communication tractable.

We found it difficult to achieve both goals without losing data and behavioral coherence. For example, we decomposed the message delivery task between the *ResponseCoordinator* and the device agents. (For a full description refer to [93].) This innovative structure allowed us to decouple protocols for delivering different types of messages from the details of the message mediums. For example, the system could have multiple *Phone* agents and an *Email* agent.

One goal of the delivery protocols was to multiplex reminders issued closely in time to be delivered in one message. We decided to put this capability in the *ResponseCoordinator* agent because we wanted the system to handle multiple devices, each of which would have its own dedicated agent. However, this separation still resulted in separately delivered reminders because a reminder could be received by *ResponseCoordinator* right after it had already dispatched the previous reminder to the *Phone* agent. To overcome this difficulty, we replicated the delivery protocol in the *Phone* agent, which defeated the purpose of decoupling.

Another problem we faced was the difficulty of scoping a lightweight agent. For example, to provide controlled access to client data, we implemented a database agent. All data read and write operations were performed by this database agent. While this approach insured database consistency, it also meant that the database agent could become a localized bottleneck.

7.4 Lesson #4: Robustness and Reliability

One benefit of the multi-agent approach is that it is distributed. However, we found that this approach does not preclude the system from having a single point of failure. Notably, the system has several agents whose primary responsibility is to provide services for other agents. Some of these service agents (e.g. *Database*, the *ResponseCoordinator*, or *Platform*) are more critical than others; if one of them fails, the whole system fails. Failures of less critical service agents (e.g. *Phone*, *UnexpectedActivity*) severely limit functionality. If a "non-service" domain agent (e.g. *Medication*, *Mobility*) fails, other parts of the system still work, although one may argue how useful the system is. Redundant capabilities (both software and hardware) is one design approach to addressing this reliability problem.

Another problem we encountered was persistence over restarts. Many of the domain agents needed a concept of recent history to make interaction decisions. If the system failed or was otherwise rebooted for some reason, agents had to reconstruct their history. Different agents reasoned over different windows of activity, and hence only localized approaches to solving this problem are appropriate.

7.5 A Final Note

The agent-based approach promised a highly open and flexible system. However, we learned that this approach still requires a very rigorous software development process, and that many challenges are yet to be addressed by the agent research community. In hindsight, we should have more seriously considered a single-threaded, component-oriented architecture. It is clear that pursuing a simpler route would have undoubtedly saved us time, money, and frustration.

8 Lessons: Ontology

The Consolidated Home Ontology in Protégé (CHOP) serves two primary purposes. First, it is a common vocabulary for I.L.S.A.-related concepts, and their relationships. Second, in conjunction with a program code generator, CHOP produces an agent communication interface between I.L.S.A.'s agent-based system components.

CHOP is an ontology containing over 800 distinct concepts. It was developed with Protégé [77], a popular visual ontology construction tool. CHOP was derived from two upper ontologies, Cyc [16] and the Suggested Upper Merged Ontology (SUMO) [72, 87]. CHOP contains concepts including support for agent configuration, logging monitoring results to a long-term store, client and environment states, and status communication.

Figure 8 shows a screen shot of the Protégé application where agents in the system are described as terms in the ontology. This illustrates the abstraction hierarchy; note that human agents are a type of biological agent, while software agents are a type of artificial agent, but both are derived from the agent class. In I.L.S.A. each client was an instance of the class humanagent, about which we know a host of facts including visual and auditory acuity, among other features.

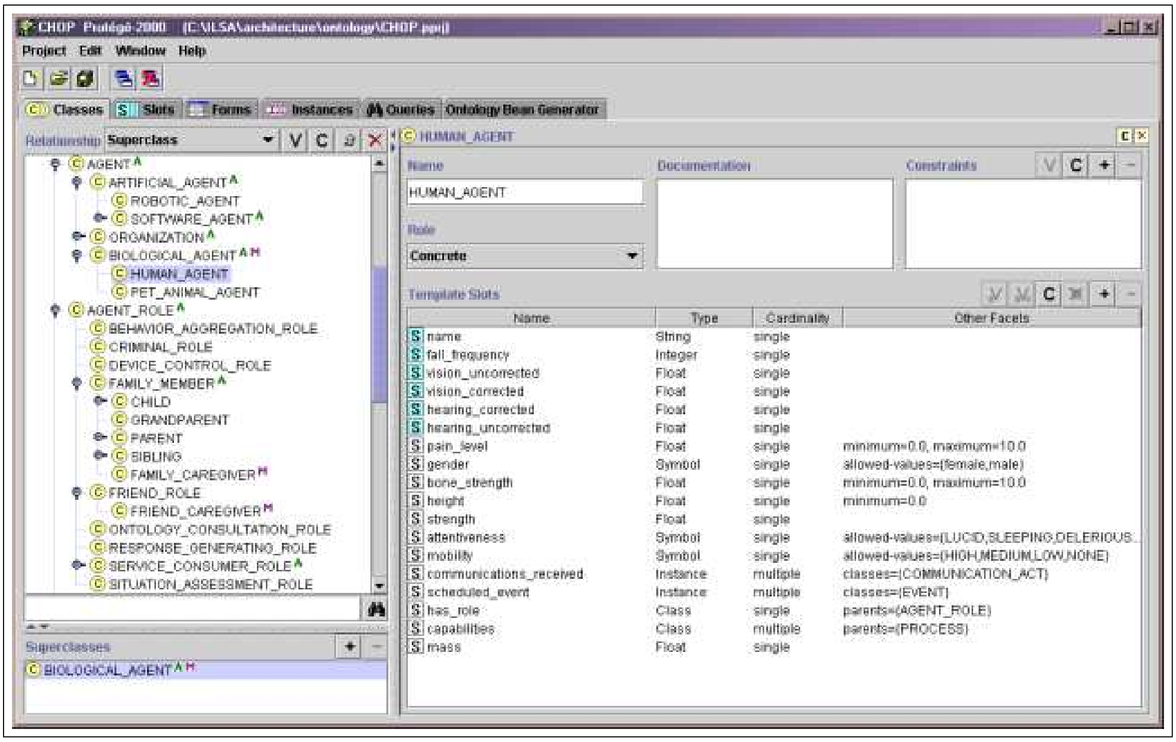

Figure 8: An example element from the I.L.S.A. Ontology.

In addition to clarifying the meaning of terms and objects in a system, the power of a formal ontology representation is that it may be used as the basis to automatically generate portions of code that are otherwise tedious. I.L.S.A.'s inter-agent communication depended upon Java classes that were auto-generated from the ontology. Taken to the furthest extreme, many system artifacts can be automatically generated using a formal ontology, including communications interfaces in multiple implementation languages, database schema, and other formal interfaces such as database access routines.

Useful lessons we derived from the creation and use of CHOP include:

- Designing one ontology for multiple purposes may mean trading lack of duplication for a steeper development learning curve.
- Don't waste ontological development effort supporting concept taxonomy or concept attributes that are not dictated by the application, even if they are relevant to the domain.
- In developing a taxonomy, be conscientious about cross-cultural compatibility.

While the use of ontologies is not novel in software design, existing ontologies did not cover the eldercare domain. While it is incomplete, CHOP represents a promising starting point for developing a reusable ontology for knowledge-based home assistance systems. To this end, CHOP has been reviewed by several academic and industry leaders, whose comments have been helpful in pushing CHOP and its derivations to be less culturally biased and more flexible regarding client configuration. We will be presenting CHOP to the Center for Aging Services and Technologies (CAST) [11] Electronic Health and Wellness Records task group. The CAST group is working on recommendations for the Health Level Seven (HL7) [40] medical record standard regarding long-term assisted care. Lessons learned in creating CHOP for I.L.S.A. have been helpful in directing the standards discussion.

Researchers interested in obtaining a copy of the ontology can send email to the authors of this paper.

9 Lessons: Automated Reasoning

At the outset of the program, a major focus was on using high-level reasoning to provide an intelligent monitoring system. To quote from our proposal:

> Experience in other domains (avionics, refineries, surgical theaters) shows that such innovations will merely produce a collection of distributed devices with localized intelligence which are not integrated, and which may actually conflict with each other in their installation and operation. Our experience shows that to consistently exhibit intelligent behavior, these networked devices will need a coordinated, situation aware, controlling intelligence.

We intended to build three main components: situation assessment and task tracking, response generation, and machine learning.

In short, our experiments in the engineer homes validated our hypothesis that this domain is very complex and lends itself very well to advanced reasoning techniques.

9.1 Lesson #1: Situation Assessment and Task Tracking

A significant risk for a monitoring system like I.L.S.A. is accurate recognition of activity. Sensors are noisy, inaccurate, and low quality. It is a significant challenge to assess the situation and recognize what activities are occurring.

We identified four kinds of reasoning that can be loosely termed "behavior recognition." These are: Clustering, Validating, Assessing, and Task Tracking. A *report* is generated by a sensor when it trips. *Clustering* collects multiple reports about the same event to generate a *hypothesized event. Validating* is the process of inferring whether a hypothesized event is an actual event. *Situation Assessment* infers the ramifications of events. *Task Tracking* is the process of inferring the goals of an agent (in our case, the elder or caregiver).

Our task tracking system was based on the Probabilistic Hostile Agent Task Tracker (PHATT) [33]. PHATT has a number of capabilities that are not available in other task tracking systems, making it uniquely suited to applying to this domain. Continuing our research on I.L.S.A., we reached the following list of requirements for task tracking systems in this kind of domain:

Abandoning Plans: All people abandon plans at one time or another: they forget what they are doing, get distracted, or decide explicitly to abandon a goal.

Hostile Agents: Not all elders are willing to have their actions observed by an assistant system; they value their independence and will therefore try to hide their actions. This unobservable action stream is a significant challenge.

Failed Actions: People will often try to achieve a goal but fail. This information could be extremely useful in this domain.

Partially Ordered Plans: People frequently work on multiple goals at the same time. The task tracker must be able to recognize interleaved plans.

Actions used for multiple effects: Often one action can achieve multiple effects; the task tracker must be able to handle this kind of *overloaded* action.

World state: Different factors in the environment can significantly affect the likelihood of the elder adopting different goals.

Multiple hypotheses: One set of actions might be contributing to more than one plan. The task tracker needs to provide a ranked list of different possibilities.

Geib [32] describes these requirements in more detail. Geib and Goldman [34] describe the specific extensions made to PHATT to incorporate reasoning about abandoned goals.

The PHATT-based intent recognition component was removed from the I.L.S.A. field study for two reasons. First, as experimental code, there were scalability and memory management issues that were not fully addressed; these have since been corrected under other funding.

Second, in an effort to reduce the deployment cost for the elders in the field study, I.L.S.A. chose to focus on a reduced set of low-cost sensors. To fully realize the potential of the task tracking system, more extensive and higher level sensor information is required.

9.2 Lesson #2: Response Generation

Response generation deals with 1) deciding *how* to respond to a given situation that exists with the elderly, and 2) *coordinating* all responses that may occur at any given moment.

Domain agents decide how to respond to a situation in a *context-free* manner. That is, they generate an appropriate response only within the context of their expertise; they do not take into account responses that other domain agents may be generating. Responses fall into four categories: reminders, notifications, alerts, and alarms. Each response category is defined by specific protocols and priorities that I.L.S.A. must follow.

Excessive and inaccurate alerts are a significant risk for this kind of monitoring system. In our field study, excessive no-motion alerts were a major cause of client and caregiver dissatisfaction. In a few cases early in our test, they created a small amount of panic when elders forgot to "turn I.L.S.A. off" when leaving the apartment. A secondary and very real risk is that the bad alerts will cause real alarms to be ignored ("never cry wolf").

These context-free messages must be prioritized, timely, and coordinated. Messages cannot be lost in a flood, and elders (and their caregivers) must overwhelmed. We chose to coordinate responses centrally rather than giving domain agents distributed access to devices. The centralized approach allows us to ensure that submission of important messages is *context-aware*:

- All responses from all domain agents must be presented on one set of devices, to one set of recipients. If we allowed domain agents to access devices directly, the recipients could be overwhelmed. Imagine receiving a dozen phone calls for different reminders at 9:00am; we wanted to merge these reminders into a single call.
- I.L.S.A. must recognize message priorities. Allowing domain agents to have distributed access to devices could cause important messages to be lost or delivered too late. For example, if the elder were to fall, the emergency call to a caregiver might be delayed behind a reminder to eat lunch.

For more detailed discussion refer to Wagner *et al.* [93].

Another novel piece of I.L.S.A.'s response generation and execution technique is the partitioning of response protocols from delivery methods. This structure allowed us to decouple protocols for delivering different types of messages from the details of the message mediums.

9.3 Lesson #3: Machine Learning

Success in this domain requires that I.L.S.A. capture the complex interactions among devices, the environment, and humans, and be particularly responsive to constant changes. Currently these systems are very inflexible, and their initial configuration is labor intensive. To adapt to changes in the client or in the environment (inevitable in this domain), we must reprogram the system. Reprogramming adds to the cost of the system and presents an inconvenience to the client.

We explored three machine learning techniques to assess their impact on I.L.S.A.'s actual operating environment:

Patterned behaviour profiles [37]: build models of what sensor firings correspond to what activities, in what order, and at what time. For example: "In 60% of the days, the Kitchen-Motion sensor fires between 18h00 and 18h30, and then the Living-Room-Motion sensor fires between 18h20 and 20h00, and then the Bedroom-Motion sensor fires between 19h45 and 22h00."

Unexpected Activity : raise alerts when activity occurs when it is probabilistically unlikely.

Schedules [50]: learn schedule information for regular activities in the clients home (e.g. medication, wake/sleep, occupancy)

Our analysis results showed that Machine Learning is a useful enhancement to even the simplest system. At a minimum, machine learning techniques can learn schedules and provide long-term trends of activity. Given a rich sensor suite, machine learning techniques can learn complex models of the environment, the elder, other people, and even the effectiveness of its own devices. These models can then be used by the system to improve its assessments and responsiveness. Machine learning techniques will allow a fielded system to:

1. tune itself to the operating environment, greatly reducing the amount of tuning and knowledge acquisition required at setup.
2. respond to changes in the users and the domain, directly reducing maintenance costs.
3. capture the user's preferences, enhancing system usability.

Two main barriers remain: evaluation and automatic incorporation of learned models into the system.

Gathering ground-truth for I.L.S.A. was not possible: users were not willing to note every activity, nor be constantly videotaped. Our evaluations were based on "eyeballing" results for plausibility and then observing whether changed system behavior was more or less acceptable to the elders and their caregivers. While short-term ground truth can be gathered, researchers will need to develop good techniques for long-term evaluation.

Currently, the elder-care industry will not accept a system that does not have a human-in-the-loop; many other industries have regulations that explicitly prohibit automatic modifications. Our approach of presenting the results to a human before incorporating them into the system was well-accepted, but is unlikely to scale to a larger community of users in its current form.

10 Lessons: User Interface

The I.L.S.A. field test system targeted two specific audiences, elderly clients and their family caregivers, using two delivery channels, web and telephone. A basic description of the interfaces we delivered is in Section 3.4. We learned several other lessons about interface design and use:

- Interfaces should be simplified. While this is a universal truth, with I.L.S.A. we found new twists for diverse audiences.
- Telephone interfaces are even harder to design than we expected.
- Elder clients were not as technology averse as anticipated, and desire an interactive system.
- Information architecture, agent architecture, and web design should be more closely integrated.

- Speech recognition and generation technology is not mature enough to handle interactions with the elderly.

Early in the program, we identified several significant interaction design risks, including intrusiveness, and incomprehensible interactions. Our best efforts to design highly usable and friendly interactions for I.L.S.A. did not completely avoid these risks as noted in the following sections.

10.1 Lesson #1: Web Page Design

Both clients and caregivers surprised us with their reactions to these interfaces: clients wanted and could use *a more complex* web interface than we expected, while caregivers were *less interested* in the data than we anticipated. (For lists of what we delivered to each audience, refer to Section 3.4.)

Client Web interface: Client interactions with the website were entirely information-pull actions. They had no explicit requirement to use the web interface, but could view it as often as they wished, or not at all. We tracked navigation through the web pages but none of the pages included interactive elements requiring data input or acknowledgement.

Clients were generally very accepting of the interface. Most viewed it daily, and were interested in the reports displayed there. 60% of clients reported feeling comfortable with the interface. They appeared to understand the data that was presented, and reported a desire to have a more interactive interface.

A risk that we identified early in the program and attempted to avoid was the use of insufficient or inappropriate communication devices. The Honeywell Web Pad™ device presented a problem for many of the elders. Even those who had prior computer experience found it easy to get lost on this non-dedicated, highly functional, wireless computer. Interaction devices deployed to elderly clients should present a simplified and dedicated interface.

Most current monitoring systems for the elderly provide personal emergency services only, and therefore generally have no interaction device other than a dedicated phone with two-way speaker capability. At the time I.L.S.A. was conceived, no other systems were attempting a high level of communication with an elderly client using a computer interface. Our experiments with I.L.S.A. show that this communication and additional interaction have the potential to be beneficial to clients, making them more active in the management of their own health, and providing additional cognitive stimuli.

Caregiver Web interface: Figure 10 shows the caregiver accesses to the website. Caregivers rarely looked past the initial status overview. They almost never looked for the trend graphs of ADL history, and to our surprise showed a general disinterest in reminders. In particular, caregivers rarely set up reminders for clients, and did not use them as designed. We believe several factors contributed to this inattention within our test group:

- No immediate health crisis
- Too busy
- Ineffective web design "hid" the features from plain view

In general, family caregivers want succinct reports, including details about today, charted history of important indicators, and links to further details. Our design gave them too little at a time.

Most systems on the market today provide little or no reporting to family caregivers. Some caregivers did use I.L.S.A. to improve their peace-of-mind by accessing up-to-the-minute reports on their client's wellbeing. While I.L.S.A.'s caregiver interface proved to be off-the-mark in terms of presentation, making more information available to family members could make even simple personal emergency systems more valuable as a long-term care tool.

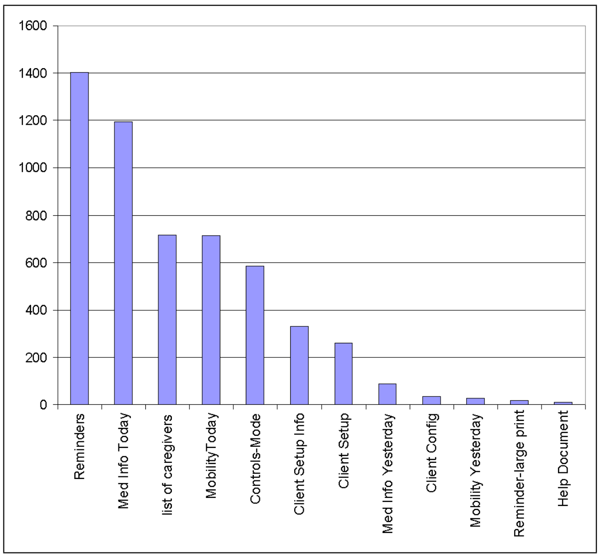

Figure 9: Web page usage on the Client User Interface.

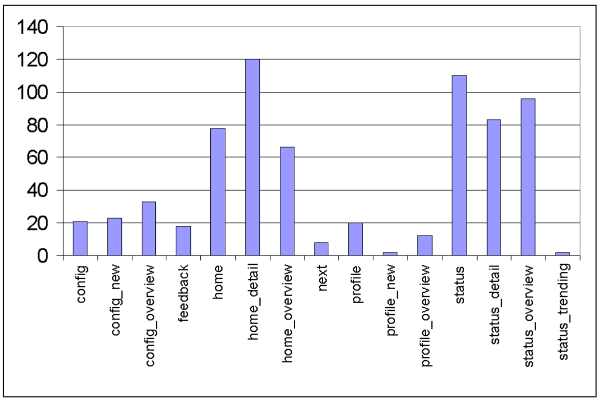

Figure 10: Web page usage on the Caregiver User Interface.

10.2 Lesson #2: Web Architecture

We made significant architecture choices before the interface design was complete. Most notably, we decided to completely separate the web interface from the agent system because of security concerns and independent development.

However, the partitioning required to keep web servers secure works against inter-process communication with processes running in the web environment. One operational impact of this design was a significant latency between changes in client configurations (via the web) and adoption of new settings by system agents. Both the web interfaces and agent system had to regularly poll the database for changes. More than simply inefficient, this structure occasionally caused scheduling conflicts within the agent system. It raised the potential for confusion, since the user interface could display information that was inconsistent with active agent parameters.

While possible, building a direct link between the agent system and the web interfaces was not a priority in reaching our project goals, though it is clearly a priority in a production system. A more integrated system would also have kept system developers more in tune with each other's progress as the system evolved.

In addition, the caregiver web site evolved from a design to support health professionals with multiple clients. The design had a complex set of disjoint client and system databases. When it was decided to test the system with only family caregivers, the databases and caregiver interface could have been simplified.

10.3 Lesson #3: Telephone Interface

The I.L.S.A. telephone interfaces consisted of message delivery—reminders to clients; alerts about possible client problems to caregivers—and a dial-in enquiry system for caregivers. The dial-in interface was an alternative to the caregiver web site.

Dial-in status enquiries: Caregivers were even less likely to use the dial-in I.L.S.A. interface than they were the web site. Only one caregiver, who did not have access to the web at work, used it regularly.

Reminder and alert delivery: Despite much literature indicating the effectiveness of telephone interfaces [29, 70], I.L.S.A. test clients universally disliked the telephone message delivery. We found that:

- Messages were perceived as computer-generated, even though a pleasant pre-recorded voice

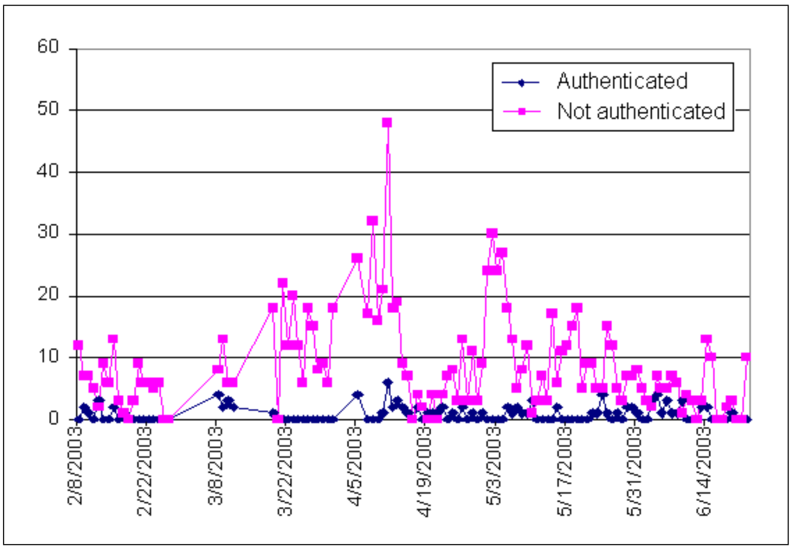

Figure 11: Unauthenticated phonecalls far outweighed authenticated ones.

was used.

- We asked for acknowledgement that we reached the correct person, e.g. "Press one if you are Lois." The cognitive and visual load required to complete this interaction was too high in many cases. (Figure 11 shows that most phone calls were not authenticated; the message was not delivered if the call was not authenticated.)
- The calls were intrusive, sometimes waking clients if they were not following their typical schedule.

Avoidance of these calls was cited as one reason for clients' compliance with their medication schedule. Unfortunately, call avoidance also resulted in attempts to fool I.L.S.A.; for example, one elder would open the medication caddy "on time," but not actually take the medication until later.

While the telephone is widely agreed to be a device that most people are comfortable using, the comfort applies only to conversations with real people. Recorded voices, even familiar voices, can be confusing. Responding to the system is stressful for some elders, and impossible for others. Still others find it difficult to talk to a real person they can't see—even "normal" telephone use with familiar people may be problematic.

These issues also tended to hold true with the caregivers in the study. While caregivers were more capable of the cognitive challenge, calls initiated by a machine were not desirable, as indicated by caregivers choosing to ignore the request for authentication, caregivers ignoring the automated messages, and caregivers panicking. Caregivers found it more acceptable to call in to an automated system at their own convenience.

10.4 Lesson #4: Speech Recognition and Delivery

At the beginning of the program, we felt strongly that a speech interface was a mandatory component for this kind of system. After exploring the technology and the problem domain in greater detail, we decided to remove the capability completely. Our decision was based on three factors:

1. It is difficult to understand an elder's voice. Not only is it difficult to locate enough microphones to get a high quality signal, but elders also have less "rich" voice streams. An elder's voice or speech patterns can change dramatically with medical issues such as a stroke, and even during the course of a day due to fatigue. Removal of dentures or simple distress will significantly reduce the ability to recognize speech during actual emergency situations.

System:	*Lois, it looks like you've fallen. Are you OK?*
Lois:	*Yes, I'm fine.*
System:	*But you haven't moved in 5 minutes.*
Lois:	*I'm OK. I'm just winded, that's all.*
System:	*Are you sure you don't want me to call for help?*
Lois:	*Yes, I'm sure.*
System:	*Maybe you'd like me to call your daughter.*
Lois:	*But I don't want to be a bother.*
System:	*I'm sure she wouldn't mind.*
Lois:	*OK, call her. But don't tell her I've fallen.*

Table 3: A sample conversation between an intelligent monitoring system and an elder.

2. Interactive speech interfaces can confuse an elder when they hear a "disembodied voice"; elders cannot cope when the system misunderstands; and elders cannot handle the delayed response time caused by (possibly remote) processing. Familiarity with the voice, or the message, does not necessarily mitigate this problem.
3. The technology is not yet ready to handle the complexity of interactions with elders. This third factor was the overriding concern: the system must not only generate dynamic syntactic structures so the elder doesn't hate the interface, but it must also understand the situation to a greater degree of accuracy than we can provide (including when to "coax" the elder). Take for example, the conversation scenario of Table 3. This conversation shows a deep understanding of the situation and its severity, in that it's not an immediate emergency, but a situation of concern. The system recognizes that Lois is reluctant to be a burden and needs to be coaxed to accept help.

Koester [51] provides additional evidence that speech interaction is unlikely to be effective in this domain. Among other issues, they point out that there is a significant "cognitive cost" to use speech recognition systems: the user must notice and correct recognition errors, learn how to speak to maximize recognition accuracy, and learn a (possibly large) set of commands to control the system. Moreover, more cognitive resources are required for speaking than for physical activity. The elders most suited to use an I.L.S.A.-like system are unlikely to be capable of meeting this challenge.

11 Lessons: System Integration

One overriding challenge throughout the program was the integration of various components of the I.L.S.A. architecture. Integration occurred at nearly every level of development and deployment. The challenge of integration was generally the most significant factor when we dropped specific capabilities from the final field test. Specific difficulties we encountered are noted in the following paragraphs.

11.1 Lesson #1: Hardware Component Integration

Throughout the program we encountered challenges in identifying the best components for the application and supporting appropriate communication between various devices. While the Honeywell components largely were designed to communicate with each other, I.L.S.A. had specific requirements that necessitated modification. Furthermore, the reliance on broadband communication and third-party, certified installers inserted a "human" integration into the equation as well.

11.2 Lesson #2: Software Component Integration

To fulfill the original vision for I.L.S.A., a number of cutting-edge technological developments already underway at Honeywell each had to be 1) modified for this domain, 2) validated for effectiveness, and 3) integrated into a cooperative whole. Some of the more advanced technologies included:

- Probabilistic Hostile Agent Task Tracker (PHATT) (Section 9.1)
- Interaction Design System [78]
- Machine Learning (Section 9.3)

To further complicate the integration of these innovative approaches, an underlying support structure for agent-based reasoning was selected. This in itself required considerable development and testing time.

By the end of Phase II of the program many of these technologies had proven their worth and applicability in preliminary testing against the installations in employee homes. At the outset of Phase III, as we coped with the reality of fielding a robust and comprehensive system to real elders, we recognized that the complete integration of all of these into one system would threaten our goals to test at least some of the features in the field.

Every point of integration adds exponentially to the potential for system failure, and equally to the difficulty of identifying the specific point of failure. As noted in Section 7, we may have saved time and effort if we had selected a single-threaded, component-oriented architecture. However, it is unlikely that the outcome would have been significantly different. The essential problems of integration and testing would have remained the same.

12 Lessons: Client Selection and Testing Lessons

In selecting I.L.S.A. clients and obtaining feedback and test results, we learned a great deal about selecting appropriate participants, and confirmed the most effective method for achieving a high response rate to surveys.

The risks we identified early in the program proved to be very real. Formal evaluation is a very expensive process; resource pressures reduced our emphasis in this area. We also had difficulty getting as many test subjects as we were hoping for, although once in the program, client retention was not an issue.

To be eligible for the study, a resident was required to be living alone, and competent in all activities of daily living (ADL), such as bathing dressing, grooming, eating, transferring, and toileting. People could be dependent in one instrumental ADL (e.g., shopping, managing money). Each person also had to identify a family member (caregiver) with access to a computer who agreed to participate in the study. Because of the sensitivity of the motion sensors, eligible persons could have only small pets.

In Minnesota, personnel at Presbyterian Homes invited residents to learning sessions about the I.L.S.A. study. Study investigators visited each facility and made presentations for all interested persons. At two facilities, we obtained a list of 23 potential clients. Dr. Krichbaum phoned interested residents and then visited each to explain the study and to obtain consent. Of the initial 23, 11 (47.8%) agreed to participate. By the time the study began, seven clients (30.4%) remained. Reasons for attrition included:

- time commitment
- some potential clients spent at least part of the year away from the state
- objections of family members

We did no statistical tests to determine if those who stayed in the study were significantly different from those who did not. The age range, however, was certainly comparable.

Our Florida clients had to meet the same conditions, and were recruited by the University of Florida's Department of Occupational Therapy. Our process yielded four clients.

12.1 Lesson #1: Selecting Participants

Our approach for selecting participants was designed to attract elders who were not too frail – very frail elders could be at risk from a prototype system. As a result, our approach netted clients who were *interested* in participating in a test, but not necessarily those that were most in *need* of the technology. As a result, more than 60% reported that I.L.S.A. was not contributing much to their independence. Furthermore, even fewer of their caregivers were appropriate. Most of them were local and felt confident of their parent's health and safety in the relatively secure environment of the living facility. None of the caregivers were uncomfortable about their client's safety, even prior to installing I.L.S.A. Consequently, the feedback we received from participating caregivers was very thin.

Clearly, to learn more about the acceptance of these systems by family or professional caregivers, and appropriately frail elders, test subject selection needs to center on caregivers with the most need, rather than clients with the most interest.

12.2 Lesson #2: Obtaining Feedback

Each week from February 1 through July 31, 2003, an investigator phoned each client. The clients were asked to comment on the usability, advantages and disadvantages/issues of using I.L.S.A. Given this collection method, feedback was consistent and complete. Similar questions were asked of family caregivers who could complete questionnaires on the web or mail them in. Three or four caregivers were very engaged and returned several surveys; most were not very engaged in the process. While we could have badgered these caregivers for results, the answers would have been predictable—those caregivers did not feel a need for I.L.S.A. in the first place.

13 Related Work and State of the Art

I.L.S.A. falls into a group of systems known as *Smart Home Technologies*. By "Smart Home Technologies," we mean systems that have sensors and actuators that monitor the occupants, communicate with each other, and intelligently support the occupants in their daily activities. For elders, tasks can range in complexity from reminders to take medication to monitoring the general deterioration in functional capability.

Many researchers have presented their visions for this kind of technology. Warren *et al* [95] describe their concepts for care delivery, sensors, smart devices and interactions among smart devices, information frameworks, information security, and patient-device interaction. Allen [3] discusses capabilities the technology should have to provide and and how that technology could be implemented. Cooper and Keating [15] present a general overview of home systems and their role in rehabilitation. Dewsbury and Edge [22, 27] discuss smart home technology and its potential care for the elderly and disabled; it also has a brief discussion on the social impact of smart homes. Miller *et al* [66] discuss the obligations of intelligent systems to elders.

Below, we present some of the related research in this area. (We specifically do not address related work in the area of ubiquitous computing.) Haigh & Yanco [39] provides a survey of related technology, and Czaja [18] describes technology opportunities and existing technology.

13.1 Human Factors

Arguably, one of the greatest challenges for systems in this domain is to provide an interface for potentially technophobic users with varying capabilities and constraints. Older adults have more difficulty learning new computer skills [17, 68], and interfaces that are poorly designed cause devices to be abandoned [2, 21, 35].

Numerous ideas have been tried to improve interfaces. Lighthouse International publishes a pair of very enlightening pamphlets on designing interfaces for people with vision problems [6, 5]. McCoy [63] summarizes many of the technologies supporting interfaces for people who have disabilities that make it difficult for them to communicate using spoken language. Pieper *et al* [74] performed a usability evaluation to improve the accessibility of the Internet, and SeniorNet [30] was a successful, early attempt to bring elders into the computer revolution. Mann *et al* [62] studied four different TV remote controls to test preferences. Controls with larger buttons, fewer functions, and higher contrast were preferred. A smart phone for centralized coordination of smart home devices [60] is currently in design. Icon selection also can dramatically improve interactions [82, 94].

Multimodal interfaces seem to be effective [90, 58] and modeling emotion seems to be a useful technique [42]. Another creative method of communicating information is through cartoon characters with facial expressions [47], although trust levels increase through a *text-based* interface, contrary to author expectations [91]. Elders also have more problems with speech [69, 85, 89], notably short term memory.

Training is also a key factor for elders [61], but the type of training is critical as well—online training is the least effective method for older adults [19].

13.2 Targeted Assistance

Numerous projects have targeted specific problems within the more general umbrella of supporting elders in their home. This section will touch only on a very small subset of projects, in part because the area is so broad, and in part because the line distinguishing "targeted assistance" from "broad-based assistance" is not firm.

Furlong [30] addressed the issue of elder isolation, discussing the success of SeniorNet, an e-community network. SeniorNet offers a member directory, email, and bulletin board. This article shows how computers can be used to increase social interaction.

An electronic community was also the subject of Gallienne *et al* [31], but in this case addressing the subject of caregiver coordination. The study examines the use of a computer network for caregivers of Alzheimer's patients; caregivers were able to share stories, ideas and, most beneficially, emotions with one another. The paper highlights how computers can be used to alleviate some of the emotional burden from caregiving.

Medication reminder systems have been shown to improve medication compliance [29]; a wide variety of systems have been built to provide this service, e.g. [9, 26, 64, 65].

Doughty [25] provides an excellent review of fall sensing technology for older adults. The article looks at different sensors, inferencing logic needed for good sensors, risk analysis, and other fall issues.

Numerous companies have developed small wearable sensors that measure vital signs, detect falls, and provide location tracking, as well as a 'panic button' feature, e.g. [24, 43, 57]. Noury *et al* [73] describe a smart fall sensor that they designed used for more general activity monitoring tasks. Medical monitoring at home is becoming a noticable trend [81].

Several efforts have also been undertaken to design "centralized controllers" for smart homes; these systems do not monitor the elder in any way [20, 61, 62]. Elders prefer remote devices with larger buttons, fewer functions and higher contrast. Custodian [22, 28] is a software tool designed to make it easier for non-technical people to utilize smart home technologies. Chatterjee [14] built an agent-based system with three device agents (TV, phone, stereo), and tried to find correlations between the interactions of those agents.

13.3 Broad-based Assistance

The systems in this section address many issues for supporting elders. A common thread is the use of passive monitoring technology to recognize behavior and raise alerts as needed. Early systems did not have the alerting capabilities, but have a clear path to this capability. Another common thread is the integration of multiple sensors.

Togawa *et al* [88, 96] was one of the first projects to use passive sensing of everyday activities to monitor subjects. Their main focus is to monitor physiological parameters, but they also monitor, for example, sleep hours, toileting habits, body weight and computer use. The systems collect data for analysis by a caregiver and do not raise alarms or automatically respond to the data in any way.

Celler *et al* [12] collects data for measuring the behaviour and functional health status of the elderly, and assessing changes in that status. Data analysis is off-line and reports are generated for participants who have demonstrated a consistent change in functional health status.

Inada *et al* [45] was perhaps the first system to incorporate the capability to contact emergency personnel whenever there is a sudden change in the patient's condition, and the patient initiates the call. The system collects biological information, physical activity, and subjective information such as complaints.

Richardson and Poulson [79, 80] describe installments of assistive home control technologies for supporting independent living. The main focus of this work was to make devices more supportive and easier to use by creating a common framework for controlling and monitoring devices, both from within the home and externally. One of the installed bases includes medical monitoring devices and raises appropriate alarms, and they call for systems that raise alarms for all appropriate 'supportive' purposes.

Glascock and Kutzik [36] similarly aims at using non-intrusive monitoring to detect functional activities of daily living. This system does not respond to the collected data in any way; the data is logged and later analyzed off-site. Their patent [53], however, covers the capability of generating a control signal in response to the collected information.

Two other significant patents in this area are Alyfuku and Hiruta [4] and Lane *et al.* [54]. Both patents describe systems that passively monitor people and can control devices based on the monitored information.

Chan *et al* incorporate the results of machine learning to control environments and automatically raise alarms. A neural network is used to learn the habits of this group of people (temperature and location) [13]. The network is trained over a given period, and then used to control the temperature of a room based on expected occupancy. The authors extend this work to recognize behavioral changes and raise alarms [86]. The authors also describe a real-time monitoring study [10].

Sixsmith [84] describes and evaluates results from an intelligent home system installed in 22 homes. The system raises alerts for "potential cause for concern"—namely when the current activity is outside a activity profile based on the average patterns of activity. The system was well-perceived by the elders and their caregivers.

Leikas *et al* [55] describe a security system for monitoring the activities of demented people at home, primarily through alarms on doors. The usability evaluation was quite thorough.

Huberman and Clearwater [41] built an agent-based, market-based temperature controller. The Intelligent Home project [56] researches multi-agent systems in the context of managing a simulated intelligent environment. The primary research focus is on resource coordination, e.g. managing the hot water supply.

The Neural Network House [71] also used neural networks to 'self-program' a home controller. The system learned the users' preferred environmental settings, and then controlled the house to meet those settings and optimize for energy conservation.

Pearl [75, 76], a joint project between the University of Pittsburgh, Carnegie Mellon University and the University of Michigan, is a mobile robotic 'nurse' assistant. Pearl guides elders through their environments and reminds them about daily activities.

NASA JSC is developing a *cognitive orthosis* to support individuals who have difficulty planning, scheduling, and carrying out tasks. The tool will monitor activities while the elder is performing them, provide additional assistance when an error occurs and provide mechanisms for intervention from third-parties [83].

The Georgia Tech Aware Home [23, 49] is a platform for a wide variety of research. Abowd *et al.* [1] describes the technological, design and engineering research challenges inherent in this domain. Research areas include computer perception, human factors, ubiquitous computing and extended monitoring.

MIT's House_n [67] is another research platform. It started as an architecture design project, namely how to design a more "elder-friendly" home. Now projects also include behavior recognition, user interfaces, and networking. Directly related to I.L.S.A. is a monitoring system for "just-in-time" context-sensitive questioning to prevent congestive heart failure [46].

The University of Washington's Assisted Cognition [48] is a relatively new project with ambitious research goals. An early paper describes a behaviour recognition and task prompting piece of the system.

Sincere Kourien, a retirement home in Japan, features robot teddy bears whose sole purpose is to watch over the elderly residents. A voice recognition system supports monitoring of patient response times to spoken questions, and raising alerts as appropriate [59].

Oatfield Estates, a residential care complex in Milwaukie, Oregon monitors and tracks medical data, weight via bed sensors, location via tags, and includes web displays for elders who can monitor their own health [8]. Vigil has fielded over 2000 dementia-care systems in multiple assisted living facilities. Their system focusses primarily on incontinence and wandering [92].

Few of these large systems have been evaluated for usability by elders; only [10, 55, 80, 84] can make this claim. Even fewer have achieved commercial viability [8, 59, 92].

14 Conclusion

We have successfully addressed each of the three significant program challenges identified in the I.L.S.A. proposal.

- We have successfully prototyped a modular and adaptive approach that can eventually support a broad customer base in widely varied and unstructured environments (Section 3).
- We have a much better understanding of what constitutes an *acceptable* monitoring system for elders and, in particular, disproved some of the assumptions made about "technophobic" elders (Section 10).
- We have a much deeper understanding of the meaning of *affordability* in the context of elder care and the factors that affect the formulation of a commercially viable offering (Section 6). We have also validated the importance of machine learning as a technique to mitigate expensive installations and ongoing adaptation (Sections 6.2 and 9.3).

Through our Knowledge Acquisition effort (Section 2), we learned what factors affect elders' independence, and identified technology opportunities. We have improved the understanding of factors that impede the delivery and acceptance of assistive technologies, and also improved our ability to overcome and mitigate these factors.

Many loosely related industry developments will push the availability and performance of access to data from the home. Similar advancements in the digitization of common home devices and appliances will increase the number of items in the home that can provide rich data about living patterns and conditions. Advancements in biotechnology and nanotechnology will provide more attractive approaches to bio-medical monitoring. By providing intelligent, affordable, usable, and expandable integration of these and other home automation devices, I.L.S.A. will support daily activities, facilitate remote interaction with family and caregivers, provide safety and security, and otherwise assist the elderly or disabled, potentially deferring nursing home care for years.

Revolutionary advances may still be a few years off. In the meantime, I.L.S.A. and similar research efforts in academia and industry will push evolutionary improvements on existing solutions and drive the elder care industry toward offering a richer array of devices and services. Technology will not replace hands-on human caregiving, but it will allow us to direct those scarce and expensive human resources more effectively.

The largest technical barriers we perceive are:

- further development, testing and verification of intelligent automation within this domain;
- development of a more effective medication management system, including 360-degree pharmaceutical services;
- development of effective and comfortable methods of communication between the system and the elderly clients.

It seems that the biggest challenge facing industry is finding a commercialization model that provides the necessary economic and social benefits at *all levels*. This requires further exploration and combination of appropriate consumers (seniors, their caregivers, and the healthcare community) with the appropriate solutions (centralized care management, communication and coordination), and of course, data acquisition and dispersion alternatives.

There is little room to dispute that a large market is emerging, but it is not yet clear where the funding will come from to support highly automated solutions like I.L.S.A. Medicare/Medicaid reimbursement of long-term care alternatives must be addressed so that funding can be directed to effective, less expensive, and more humane alternatives to institutionalization.

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