A Reference Architecture for Building Cyber Physical Space for Independent/Assisted Living

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A. Motivation

Motivation: The United States has a long history of success in the science of computing, hosting some of the earliest computers (such as ILLIAC) and computer-assisted program of “intelligent” instructions (such as PLATO). The early computers were very large, occupying entire buildings, and computer scientists that built and used them to develop some of the early breakthroughs in computer technologies and applications literally worked inside the computer. In many aspects, today's technology brings us back to “life inside a computer.” With advances in wired and wireless networking, handheld and embedded computer systems, sensor and actuator technologies, our environment has been equipped with a networked heterogeneous and dynamic array of sensors, actuators, computing devices and controllers capable of acquiring a wide array of different attributes. With the enormous amount of information collected everywhere via these devices, one can better interact and make sense of the environment and support a variety of applications. In some sense, we live inside a huge, rapidly growing, intelligent cyber physical space.

One potential cyber physical space application that has tremendous social and economical impacts is to help elderly people with their independent living. According to MIT's magazine TECHNOLOGY REVIEW, July/August 2003, ```
Because of the aging of baby boomers, in the United States alone the number of people over age 65 is expected to hit 70 million by 2030, doubling from 35 million in 2000.” Along with the increase of population of elderly people, the expenditures of the United States for health-care will grow projecting to rise to 15.9% of the GDP ($2.6 trillion) by 2010 (Digital 4Sight's Healthcare Industry Study). This, coupled with the move away from the nuclear family household and the increasingly youth-oriented society, has two consequences: first, many elderly people will be left to their own devices in receiving health care and satisfaction from life; second, many of them are also expected to living alone or in assisted living facilities. According to a report by National Institute on Aging, only 10% of elderly people of age 65-85 and 25% of those of age 85 and above in the United States are institutionalized. Because of the deteriorating capabilities to sense and interact with the environment, such as memory, eye sight, hearing, dexterity and mobility, elderly people often live with significantly degraded life quality. Without modest assistance, they often cannot keep up with their schedule and at times are unable to call for help after a serious fall or illness.

What is needed is an open, wireless-enabled cyber physical space that restores elderly people’s deteriorating capabilities to sense and interact with the environment and enables them to regain their capability of independent living. To develop a feel of how such an environment would facilitate independent/assisted living, consider how elderly people with chronic diseases (such as diabetes) monitor their health condition, take medication, and carry out daily routines. A typical diabetes patient is required to measure his/her glucose level (with the OneTouch device, for example) twice a day and keep track of their weight change. He/she is also required to take oral medication and/or insulin injection before meals and/or before bedtime. Very often, a patient would fail to do so because of forgetfulness or negligence. He/she may also have problems locating their personal belongings and/or medical bottles. The patient is also required to pay a monthly/quarterly clinic visit with his/her OneTouch device and weight log. It is at that time when the glucose levels/weights are retrieved and analyzed by healthcare providers, the dose of medication (e.g., the units of insulin injection and/or the dose of water pills) adjusted, and/or additional medical instructions given. Should the patient’s health condition deteriorates between clinic visits, no medical
advices/procedures can be given. If a smart cyber physical space existed in the home/assisted living environment, then

(a) The environment can obtain from a monitoring center (located on the Internet, to which health care providers have access) updated prescription and appointment records of residents through secure channels. When it is time for the patient to carry out his/her time driven routines, such as taking medication or vital signs, the environment locates active wireless-enabled devices (e.g., TVs, cell phones, wearable headsets, and/or active badges) in range, and sends reminder messages to one or more devices that are in the proximity of the patient. Whether or not these routines are followed as advised is then detected in a non-intrusive manner by exploiting wireless localization technologies such as Ubisense or RFID.

(b) The patient can measure his/her vital signs (e.g., weight, glucose level, blood pressure, arterial oxyhemoglobin saturation level, and pulses) with various wireless-enabled medical meters. The measurement results are then transmitted through the cyber physical space to the monitoring center, where healthcare providers can check whether or not vital signs have been taken as scheduled and analyze measurement results at the time granularity smaller than monthly/quarterly. Have certain vital sign(s) been dangerously high/low, proper medical instructions can be given much earlier before medical complication develops.

(c) With the use of wearable wireless-enabled accelerometers and wireless localization techniques, the assisted living environment can profile residents' movement in a privacy preserving manner (e.g., without the use of surveillance video cameras) and detect early warning signs for depression (stop taking medication regularly, giving up routine activities, or staying in bed for long periods of time), other chronic diseases such as Parkinson’s disease and Alzheimer’s disease, and/or unexpected falls.

(d) Personal belongings such as eyeglasses, hearing aids, wearable accelerometers, and key chains can be attached with tags, and located through the use of Ubisense/RFID readers. When a patient cannot find his/her belongings (because of forgetfulness), he/she can issue a simple vocal command to the butler PC which then schedules the RFID/Ubisense readers to scan the environment and help locate the object.

(e) The environment can also enable, with different levels of information disclosure, designated relatives and friends of residents to keep track of the status of their loved ones. Personal touch can be preserved by allowing relatives/friends to interact with residents asynchronously and leaving audio/video/text messages in the environment.

(f) In case of need for emergency attention (e.g., the blood pressure/sugar has been dangerously high/low, and/or the resident has been detected via wireless localization techniques to be immobile on the floor for an unreasonably long time), the environment establishes real-time communication channels to notify on-site caregivers (in the case of assisted living) or healthcare provider/designated relatives (in the case of independent living), and facilitate transmission of EKG and other measures in real time.

B. Technical Objectives

With rapid technology advances in sensing (e.g., Ubisense/RFID techniques for tracking, presence identification, and localization), computing, and wireless networking (e.g., Bluetooth/IEEE 802.11 enabled devices and infrared-equipped remote controls), many component technologies needed for realizing such a cyber physical space for independent/assisted living are already available. What is missing is the architectural design, and its scientific foundation, of an open, robust, secure and easily deployable environment that allows disparate technologies, software components, and wireless devices to operate with predictable properties. As shown in Figure 1, the architecture should, on the one hand, provide functionalities required to provide pervasive healthcare services, e.g., sensing, monitoring, localization, wireless communication, and event management, and on the other hand, fulfill multi-dimensional performance requirements:

1) Ease of use and ease of deployment: Given the fact that a majority of elderly people are not technically suave, the user interfaces provided in the environment should be easy-to-use, safe, and accommodating with respect to user mistakes. Deployment, configuration, and maintenance of the environment should also be automated to the maximal extent possible, and require minimum intervention of residents.

2) Security and privacy: In spite of the intended openness in the environment, devices should be introduced into the environment without compromising security and privacy. This, coupled with the fact that wireless networking is
the predominant communication paradigm, implies that authentication and wireless security should be built-in functions in the initial stage of architectural design. Medical and personal data collected in the environment should also be protected with different levels of information disclosure to different roles (healthcare providers, medical team, designated relatives, and residents themselves) in the environment.

3) **Quality-of-service provisioning**: In the presence of various forms of workload dynamics, ranging from transmission of reminder messages, monitoring/measurement data, audio/text commands, to time-critical multimedia streams supporting tele-medicine, different levels of *quality of service (QoS)* should be provided on an end-to-end basis to applications subject to their timing, reliability and criticality requirements. This requires QoS provisioning not only in the local wireless LAN/PAN environment but also on the backbone Internet.

4) **Evolvability and interoperability**: To significantly reduce the system integration and deployment time and promote industry standardization, the environment should be open with well defined interfaces and support a wide variety of newly emerging, third-party devices in a plug-and-play fashion.

5) **Safety, robustness and availability**: Critical services should be failure safe, and delivered in spite of failures of useful but non-critical services. Moreover, the environment as a whole should be *ubiquitously* available and resilient to a wide variety of failure modes.

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**Figure 1: Integration of sensing/communication/computing**

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**C. Example Reference Architecture**

Researchers in the Department of Computer Science at University of Illinois have engaged in the design, implementation, and evaluation of an open, wireless-enabled cyber physical space for assisting elderly people with their independent living. They propose a *drop-box* architecture (Figure 2) in which an assisted-living device, called *Authentication Manager for You (AMY)*, is co-located with a home PC called the *butler*, and equipped with various wireless interface cards (IEEE 802.11, Bluetooth, Ultra Wide Band, and Infrared). AMY, along with the butler, hosts the proposed software environment and serves as the intelligence for the environment. It also serves as the gateway to a monitoring center (at which healthcare providers and medical experts can retrieve/analyze data, monitor the environment, and give orders if necessary) over the Internet.

This drop-box architecture has fulfilled the aforementioned architectural requirements:

1.) **Ease of deployment**: Similar to the *ADT home security system*, only a *pre-configured* drop box, AMY, along with the butler software, needs to be installed in the environment. The system can be re-configured through user-friendly, error-accommodating, web-based interfaces at the butler PC. For example, residents can select their preferred devices for reminder messages, whether or not reminder messages should be resent in the lack of
corresponding daily activities. They can also specify whom may view their medical data and at what level. The new configuration can then be automatically uploaded to AMY and the monitoring center.

Figure 2. The software architecture that realizes the functionalities required for assisted living

Analytically provable security: With only a few entities equipped with control intelligence (AMY, the butler, and the monitoring center), security can be ensured by augmenting these entities with robust authentication and security mechanisms, and argued in an analytically provable manner. In particular, AMY governs all the devices present in the environment. Devices can be introduced into the environment only after they are properly authenticated by AMY. These devices include the butler PC and various wireless-enabled medical devices, such as the blood pressure meter, oximeter, glucose meter, and ECG heart rate monitor. All the data transmissions locally in the wireless environment or over the Internet will be protected via link-level authentication mechanisms (such as WPA-2) and/or application-level security mechanisms (such as SOAP).

Privacy preservation with role-based trust management: The monitoring center serves as a global intelligence and data repository. With role-based trust management and access control, clinicians, healthcare providers, and/or designated relatives can gain access to various medical, localization and monitoring data, with different levels of information disclosure, thus preserving privacy. Various medical/movement/monitoring data can be profiled and analyzed, and medical/healthcare decisions can be made. In case of need, medical advices can be given and in-home nurses be dispatched.

Capability of QoS provisioning: Figure 3 depicts the technical view of how vital sign measurements are transported via Bluetooth to a PDA (which acts as an integrated part of a smart medical device)\(^1\), via IEEE 802.11 to AMY, and then via the Internet to the monitoring center. With the butler PC being the local intelligence (and governing local wireless resources) and AMY being the gateway to the monitoring center, resources can be budgeted and scheduled in the local wireless environment and on the Internet, respectively, thus ensuring end-to-end QoS.

Interoperability and openness: The butler software is responsible for detecting wireless devices in range, for activating RFID or Ubisense readers to scan and monitor the environment, and for transporting monitoring/localization data through AMY to the monitoring center. To allow newly-emerging, third-party devices to be readily plugged into the system, a device integration layer is laid on top of the various proprietary device drivers on the butler PC or smart medical devices (Figure 4) and export a generic, open network API,

getNetworkInput/OutputStream (String networkStackType, String qosRequest, StringBuffer qosAllocated, String devAddress),

to higher layers. This allows applications to be developed in a device-oblivious manner. The device integration layer is responsible for (a) detecting devices in range; (b) translating QoS requirements passed from the higher layer into protocol-specific parameters; (c) exercising admission control and providing, if possible, QoS requested by the higher layer; and (d) detecting and mitigating wireless interference. As shown in Figure 5, the device integration layer embodies several modules, each of which is responsible for realizing

\(^1\)Note that Internet-capable, smart medical devices are not currently available. As such, we “interface” Bluetooth-enabled medical devices with PDAs and leverage the programming environment, as well as the IEEE 802.11 interface, available on PDAs for data transport to the Internet.
one aforementioned function. When a new device is introduced into the environment, new function modules will be instantiated for this device, thus allowing the device to be *seamlessly* integrated into the environment.

![Diagram](image)

Figure 3. A technical view of how the medical data is transported to the monitoring center (when AMY is in the normal operation mode)

![Diagram](image)

Figure 4. The device integration layer.

6.) **Ubiquitous availability and robustness:** The environment ensures that a set of critical services provided in the cyber physical space remain available even when the resident is away from his/her home/assisted living environment or when AMY or the butler PC is down. This is achieved by enabling wireless medical devices or the butler PC (if it is not down) to automatically detect the unavailability of AMY and to use cell phones as *portable* AMY with a reduced set of functionalities. The *dial-up networking profile (DUN)* service available at most of the Motorola cell phones can readily instrument cell phones to act as data forwarders, and *Bluetooth pairing with PIN codes* can be leveraged to provide authentication with link keys. Figure 5 depicts the technical view of how medical data is transported *when Amy is replaced by a cell phone*.

One important feature that has been considered when the battery-powered cell phone is introduced as the wireless modem is energy efficiency. As transport of a large amount of data becomes prohibitively energy
inefficient, intelligent information fusion and acquisition applications have been programmed on a cell phone. Instead of passively relaying all the measurement data, the cell phone is instrumented to infer the status of the resident based on a set of pre-specified rules, and only transport readings to the monitoring center when abnormal situations are identified. The set of pre-specified rules can be downloaded from the monitoring center to the phones, and can be either simply threshold-based or derived based on a more complicated correlation between readings from different devices. Moreover, the cell phone is instrumented to command, based on the outcome of data fusion, Bluetooth-enabled medical devices to adjust their sampling frequency or working mode. This enables intelligent data acquisition with desirable time granularity from smart medical devices.

Various services can be realized by installing various applications and databases on the butler PC and the PDA. For example, the time-driven reminder service (Scenario (a) in Section 1) can be provisioned by having a reminder application installed at the butler PC. It finds, at scheduled time instants, a proper wireless device in range and issues reminder messages (e.g., time to take medicine) in an appropriate form (e.g., voice messages to the Bluetooth-enabled headset). The reminder application will also schedule the RFID/Ubisense readers to scan the environment and keep track of the resident's response (e.g., whether or not the medicine has been taken). The object localization service (Scenario (d) in Section 1) can be provisioned in a similar manner. Upon receipt of vocal commands, the object localization application either (i) queries the device/object location database or (ii) schedules RFID/Ubisense reader scanning events to find the whereabouts of the requested object. Then the application can send a response message to a proper wireless device that is either in range or specified by the resident.

Figure 5. A technical view of how medical data is transported to the monitoring center (when Amy is not available).

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