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An Assisted Living Oriented Information System Based on a Residential Wireless Sensor Network

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Abstract—**This paper deals with a new medical information system called *Alarm Net* designed for smart healthcare. Based on an advanced Wireless Sensor Network (WSN), it specifically targets assisted-living residents and others who may benefit from continuous and remote health monitoring. We present the advantages, objectives, and status of the system built at the Department of Computer Science at UVA. Early results of the prototype suggest a strong potential for WSNs to open new research perspectives for ad hoc deployment of multi-modal sensors and improved quality of medical care.**

I. INTRODUCTION

As the world's population ages, those suffering from diseases of the elderly will increase. In-home and nursing-home pervasive networks may assist residents and their caregivers by providing continuous medical monitoring, memory enhancement, control of home appliances, medical data access, and emergency communication. Monitoring the resident's activity of the daily living (ADL) for example is a means to estimate his/her autonomy to live alone at home [1].

Researchers in computer, networking, and medical fields are working to make the broad vision of smart healthcare possible [2-10]. For example, some of them are devoted to continuous medical monitoring for degenerative diseases like Alzheimer's, Parkinson's or similar cognitive disorders [6]. Other projects such as "CodeBlue" at Harvard extend WSNs for medical applications in disasters [7]. Some focus on high-bandwidth, sensor-rich environments [3].

This paper presents an emerging system design oriented around remote, continuous medical monitoring using wireless sensor networks. Its advantages for in-home monitoring and our long-term objectives are described in the next section. Part III describes the vision of our final architecture. Parts IV and V deal, respectively, with technological choices and the current status of the system. Part VI describes our various ongoing research topics.

II. MAIN OBJECTIVES OF THE MEDICAL TESTBED

We are developing a residential network for smart healthcare that will open up new opportunities for continuous and long-term monitoring of assisted and independent-living residents [11, 12]. While preserving resident autonomy, comfort and privacy, enhancing quality of life and security, the network manages an audit trail and continuous medical history. Only authorized users of the system can perform consultations from the medical history, which will be accessible from the medical center or directly from the patient environment. Unobtrusive area and environmental sensors combine with wearable interactive devices to evaluate the health of spaces and the people who inhabit them. Authorized care providers may monitor residents' health and life habits, watch for chronic pathologies and continuously monitor medication and nutrition.

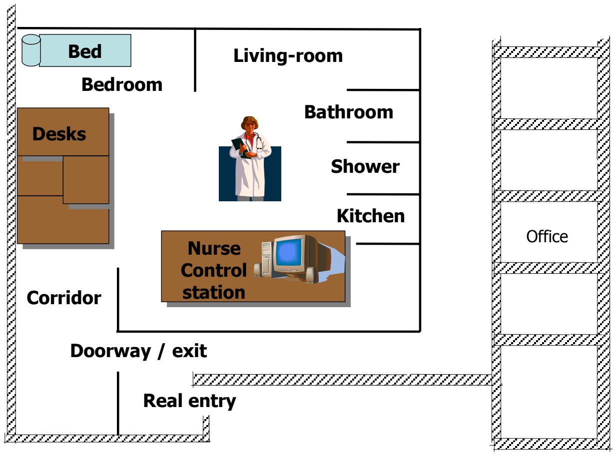

Figure 1: Layout of the Smart Living Space at UVA.

Multiple patients and their resident family members as well as visitors are differentiated for sensing tasks and access privileges.

High costs of initial installation and retrofitting are avoided by using ad hoc, self-managing networks. Based on the fundamental elements of future medical applications (integration with existing medical practice and technology, real-time and long-term monitoring, wearable sensors and assistance to chronic patients, elders or handicapped people), our wireless system will extend healthcare from the traditional clinical hospital setting to nursing and retirement homes, enabling telecare without the prohibitive costs of retrofitting existing structures. Figure 1 shows the layout of the experimental laboratory.

The architecture is multi-tiered, with heterogeneous devices ranging from lightweight sensors, to mobile components, and more powerful stationary devices.

The advantages of a WSN are numerous for smart healthcare, as it provides the following important properties:

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1. **Portability and unobtrusiveness**. Small devices collect data and communicate wirelessly, operating with minimal patient input. They may be carried on the body or deeply embedded in the environment. Unobtrusiveness helps with patient acceptance and minimizes confounding measurement effects. Since monitoring is done in the living space, the patient travels less often, which is safer and more convenient.
2. **Ease of deployment and scalability**. Devices can be deployed in potentially large quantities with dramatically less complexity and cost compared to wired networks. Existing structures, particularly old ones, can be easily augmented with a WSN network whereas wired installations would be expensive and impractical. Devices are placed in the living space and turned on. They then self-organize and calibrate automatically.
3. **Real-time and always-on**. Physiological and environmental data can be monitored continuously, allowing real-time response by emergency or healthcare workers. The data collected form a health journal, and are valuable for filling in gaps in the traditional patient history. Even though the network as a whole is always-on, individual sensors still must conserve energy through smart power management and on-demand activation.
4. **Reconfiguration and self-organization**. Since there is no fixed installation, adding and removing sensors instantly reconfigures the network. Doctors may re-target the mission of the network as medical needs change. Sensors self-organize to form routing paths, collaborate on data processing, and establish hierarchies.

III. ARCHITECTURE AND CAPABILITIES

The medical sensor network system integrates heterogeneous devices, some wearable on the patient and some placed inside the living space. Together they inform the healthcare provider about the health status of the resident. Data is collected, aggregated, pre-processed, stored, and acted upon using a variety of sensors and devices in the architecture (activity sensors, physiological sensors, environmental sensor, pressure sensor, RFID tags, pollution sensors, floor sensor, etc.). Multiple body networks may be present in a single system. Traditional healthcare provider networks may connect to the system by a residential gateway, or directly to its distributed databases. Some elements of the network are mobile, while others are stationary. Some can use line power, but others depend on batteries. If any fixed computing or communications infrastructure is present it can be used, but the system can be deployed into existing structures without retrofitting.

The components of the architecture are shown in Figure 2, dividing devices into strata based on their roles and physical interconnect. Each tier of the architecture is described below.

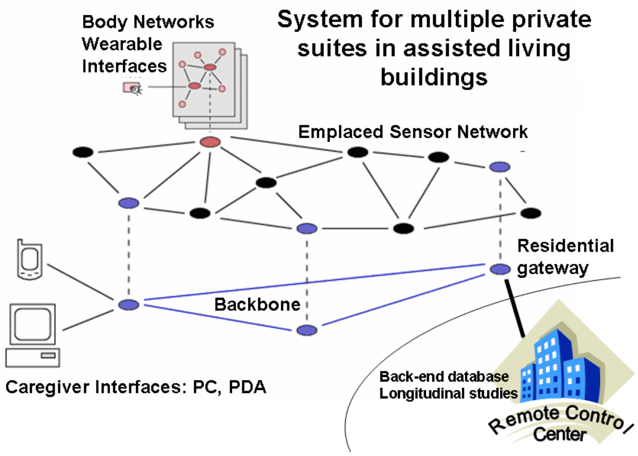

Figure 2: Multi-tiered system architecture, showing physical connectivity.

1. **Body Network and front-ends**. This network comprises tiny portable devices equipped with a variety of sensors (such as heart-rate, heart-rhythm, temperature, oximeter, accelerometer), and performs biophysical monitoring, patient identification, location detection, and other desired tasks. These devices are small enough to be worn comfortably for a long time. Their energy consumption should also be optimized so that the battery is not required to be changed regularly. They may use "kinetic" recharging. Actuators notify the wearer of important messages from an external entity. For example, an actuator can remind an early Alzheimer patient to check the oven because sensors detect an abnormally high temperature. Or, a tone may indicate that it is time to take medication. The sensors and actuators in the body network are able to communicate among themselves. A node in the body network is designated as the gateway to the emplaced sensor network. Due to size and energy constraints, nodes in this network have little processing and storage capabilities. More details about the particular body networks initially developed in the medical testbed are available [12]. Other researchers investigate the domain of aware mobile computing based on wearable devices [13].
2. **Emplaced Sensor Network**. This network includes sensor devices deployed in the assisted living environment (rooms, hallways, units, furniture) to support sensing and monitoring, including: motion, video camera, temperature, humidity, acoustic, smoke, dust, gas, etc. All devices are connected to a more resourceful backbone. Sensors communicate wirelessly using multi-hop routing and may use either wired or battery power. Nodes in this network may vary in their capabilities, but generally do not perform extensive calculation or store much data. The sensor network interfaces to multiple body networks, seamlessly managing hand-off of reported data and maintaining patient presence information.
3. **Backbone**. A backbone network connects traditional

systems, such as PDAs, PCs, and in-network databases, to the emplaced sensor network. It also connects discontiguous sensor nodes by a high-speed relay for efficient routing. The backbone may communicate wirelessly or may overlay onto an existing wired infrastructure. Nodes possess significant storage and computation capability, for query processing and location services. Yet, their number, depending on the topology of the building, is minimized to reduce cost. The backbone also provides the spatial context for real-time patient monitoring, and other critical research issues, as described in section VI.

4. **In-network and Back-end Databases**. One or more nodes connected to the backbone are dedicated in-network databases for real-time processing and temporary caching. If necessary, nodes on the backbone may serve as in-network databases themselves. Back-end databases are located at the medical center for long-term archiving, monitoring and data mining for longitudinal studies. Depending on the information stored in the patient medical history, old records can be removed, upgraded or appended with the new incoming data.
5. **Human Interfaces**. Patients and caregivers interface with the network using PDAs, PCs, or wearable devices. These are used for data management, querying, object location, memory aids, and configuration, depending on who is accessing the system and for what purpose. Limited interactions are supported with the on-body sensors and control aids. These may provide memory aids, alerts, and an emergency communication channel. PDAs and PCs provide richer interfaces to real-time and historical data. Caregivers use these to specify medical sensing tasks and to view important data.

IV. TECHNOLOGICAL CHOICES

The motes forming the wireless sensor network run TinyOS [14], an operating system for sensor network nodes, and are commercialized by Crossbow [15]. Among several WSN devices embedding TinyOS (MicaZ, Mica2, Mica2dot, Telos, Pluto), we chose the MicaZ motes. They use a ZigBee-compliant (802.15.4) wireless protocol for communication, and are a good trade-off with our requirements for the system. They have high radio bandwidth (250Kbps), a large flash data program memory (128KB), a 512 KB flash data memory and can be powered with 2 AA batteries providing a long lifetime with an appropriate power management scheme. They also offer a large range of compatible sensors. These motes are programmed using the language nesC which is an extension of the C language for networked systems running TinyOS.

We chose a single board computer called Stargate [15] to constitute the nodes of the backbone. Stargates run Embedded Linux and have more power and capabilities than the motes. They offer various interfaces such as Ethernet, USB, etc. and can be used as residential gateways. These technological choices permit us to pursue some WSN research topics within the medical testbed, and to open connections with other testbeds using the same technology.

V. STATUS OF THE CURRENT SYSTEM

A. Overview of the implemented system

We simulate a smart nursing suite in our lab (Figure 1) using some partitions dividing the experimental platform into multiple rooms. Motion sensors are positioned on the walls in every room to detect movements and presence in the entire smart environment. As soon as the motion event is detected, the motion sensors, interfaced with MicaZ, send the data packet through the ZigBee-compliant Network to the back-end of the system via a gateway. Currently, time-stamping is done at the PC when motion events are received. In the back-end, data are stored in a MySQL database which is currently located in the technical area of the experimental platform. A friendly user interface on the Nurse Control Station manages the authentication of the users who can, depending on their roles, retrieve and display different information from the database. For example, doctors can poll the database in real-time to see the location of the patient is and to display body tracking history (visit frequencies per room, the lapses of time the resident spends in every room and the last motion events). In parallel, the same network manages a preliminary query management system directly distributed between the sensor devices and the nurse control station, or PDA. The patient's vital signs and the environmental conditions can be collected in this way in real-time. In the future, the system will use a straightforward query management architecture centralized on Stargates and distributed from front to the back-end of the system. Queries will be acknowledged in Stargate depending on privacy, alert level, etc.

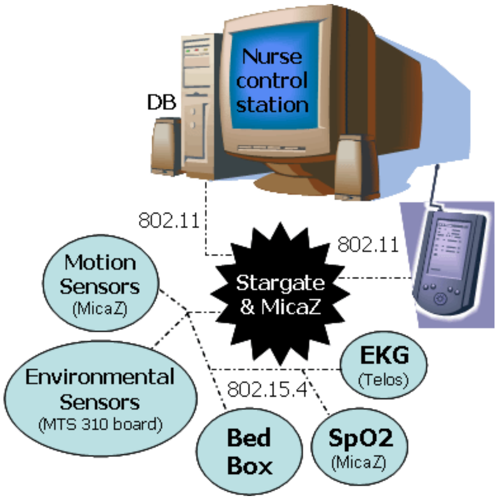

Figure 3: Overview of the operational system.

A summary of system requirements is shown in Table I.

TABLE I
SYSTEM REQUIREMENTS

Requirements	Operational Yes/No
Query management	Yes
Power management	No
Authentication	Yes
Data privacy	No
Multiple patients	No
Real-time (delays < 0.3sec)	Yes

B. *Data acquisition*

1. **Motion sensor**. We have adapted a low-cost sensor module (model RMS18 IR) originally designed for X10 systems in home automation [16] that is capable of detecting motion and ambient light levels. The module also has a simple one-button and LED user interface for testing and diagnostics. It is interfaced to a MicaZ wireless sensor node (event based) that processes the sensor data using interrupts and forwards the information through the wireless network. A set of such modules is used to track human presence in every room of the simulated smart health home. The number of motion firings can be locally filtered or computed using a query processor to evaluate accurately the presence of a resident within a room.
2. **Body network**. A wearable WSN service with MicaZ motes embedded in a jacket was implemented to record human activities such as walking, eating and stillness using three 2-axis accelerometers. It also incorporates a GPS to track the outdoor location of the patient if he roams outside the living space. The recorded activity data is subsequently uploaded through an access point for archiving, from which past human activities and locations can be reconstructed.
3. **Indoor temperature and luminosity sensor**. These pollable sensors (cf. MTS310 electronic board [15]), give the environmental conditions of the habitat and are also connected to the backbone via MicaZ.
4. **Bed sensor**. The bed sensor, developed by the Medical Automation Research Center (MARC), is based on an air bladder strip located on the bed, which measures the breathing rate, heart rate and agitation of a patient [2].
5. **Pulse-oximeter and EKG**. These sensors were developed by Harvard University [7]. They are wearable, connecting to MicaZ and Telos devices, and collect patient vital signs. Heart rate (HR), heartbeat events, oxygen saturation (SpO_2), and electrocardiogram (ECG) are available.

C. *Backbone infrastructure*

Our preliminary version of the system uses a backbone based on a single Stargate gateway. The gateway is interfaced to a MicaZ mote via a serial link, and both MicaZ and Stargate run serial forwarders. We use single hop routing within a range of 20 to 30 meters indoors, covering the main area of interest. Currently, the system does not consider network arbitration, acknowledgments, routing, data aggregation and power management (a richer WSN including these functionalities is an ongoing project). Also, a multi-hop protocol is envisioned to access multiple floors and reduce power consumption.

Other systems are based on fieldbus to monitor resident activity in the Smart Houses domain [9]. For example, the CAN network (Controller Area Network – ISO11898) has advantages such as automatic integration of services (e.g. node to node message integrity checks, control field or error detection mechanisms) directly into the OSI model's layers (ISO7498 Open Systems Interconnection).

D. *Database management and data mining*

We adopt MySQL database to serve as a back-end data store for the entire system. It is located on a PC connected to the backbone, and stores all the information coming from the infrastructure for longitudinal studies and offline analysis. A medical application based on the resident daily life rhythm (circadian activity rhythm - CAR) analyses the distribution of time lapses spent by the resident to model his/her activity pattern within each room of the home. Ongoing clinical experiments with our collaboration at the medical school at UVA [2] aim at validating this application for older adults in assisted-living residences. Ideally, we hope to detect behavioral anomalies with this application and to predict health decline or pathologies in the early stages [17].

E. *Graphical user interfaces*

Interfaces with residents, healthcare providers, and technicians have different requirements. Each must present an appropriate interface for performing the intended tasks, while conforming to the constraints imposed by form factor and usability. Currently, the system offers four different GUIs. The first is located on the local nurse control station, and it tracks the motion of the resident using motion activations.

A second GUI (Figure 4), which runs on a PDA, permits a caregiver to request real-time environmental conditions of the living space and the vital signs of the resident. It uses a query management system distributed among the PDA, Stargate and the sensor devices. The interface graphically presents requested data for clear consumption by the user.

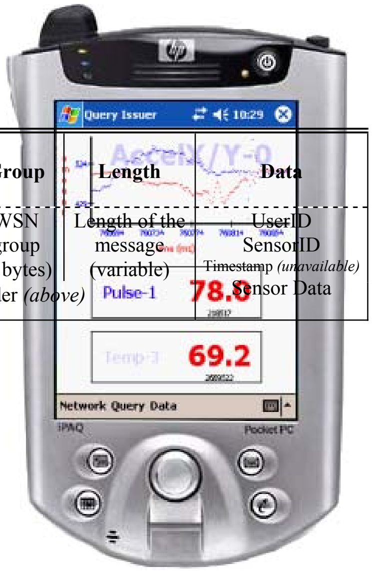

Figure 4: A GUI displays accelerometer data, patient pulse-rate, and environmental temperature.

An LCD interface board was also designed for the MicaZ for wearable applications. It presents sensor readings, reminders and queries, and can accept rudimentary inputs from the wearer. An SD card can also be plugged into the mote to extend its inherent data memory storage capacity (see section IV) to collect large amounts of data. For example, a doctor could use it in a patient suite to download his/her physiological data collected during an observation night and to upload them later at the medical center.

F. Evaluation

A one week experiment proved the robustness, accuracy and reliability of the system. The experiment was based on the motion motes programmed to send any movement detected within the experimental platform at any time during the week. The lab remained closed during this period of time and nobody was authorized to enter. This total absence of activity inside the lab permitted us to estimate the rate of false detections which was 0% with the experimental conditions of the lab (presence of an AC and no windows). This experiment also showed us the necessity to establish a power management scheme to prolong the lifetime of the sensors. Other technical tests in situ at various levels of the architecture were performed. For instance, real-time body tracking on the control station is correctly displayed when a resident walks in the smart area. This demonstrated the validity of the full acquisition chain from front to back-end. Also, at the WSN level, data packets are currently broadcasted in one hop to the whole WSN. Sending information is coded in the data part of the TinyOS standard payload as described in Table II. The transmission delay from front to back-end last was less than half a second which is a very good performance. Next experiments will investigate the information loss, throughput and jitter.

TABLE II

CURRENT TINYOS PACKET DATA FORMAT CONFIGURATION

Destination address	**Message type**	**Group**	**Length**	**Data**
Multicast (2 bytes)	Configure message type (1 byte)	WSN group (2 bytes)	Length of the message (variable)	UserID SensorID Timestamp *(unavailable)*
TinyOS Message Header *(above)*				Sensor Data

VI. ONGOING RESEARCH TOPICS

1. **Multi-modal data association and multiple residents**. Data association is a way to know "who is doing what?" in a system where biometric identification is not always accessible (for example, when the patient forgets to wear an endo-sensor embedding an ID) and with multiple actors present, such as an assisted-living community. It permits us to recognize the right person among others when he is responsible for a triggered event. This is indispensable for avoiding medical errors in the future and properly attributing diagnostics. Consequently, dedicated sensors and data association algorithms, based on techniques such as Bayesian Networks, must be developed to increase reliability of data.
2. **Data integrity**. When the data association mechanisms are not sufficient, or integrity is considered critically important, some functionalities of the system can be disabled. This preserves only the data which can claim a high degree of confidence. In an environment where false alarms cannot be tolerated, there is a tradeoff between accuracy and availability.
3. **Privacy**. The system is monitoring and collecting patient data that is subject to privacy policies. For example, the patient may decide not to reveal the monitored data of certain sensors until it is vital to determine a diagnosis and therefore authorized by the patient at the time of a visit to a doctor. Alternatively, the patient may decide to let the data be used for a statistical study without revealing his identity. We are establishing an adaptive privacy scheme, interacting from front to back-end of the system based on the different actors involved in assisted living and using dedicated WSN protocols and semantics.
4. **Security**
Security mechanisms must be throughout the system. It is important to consider security in the system since the ZigBee-compliant network is exposed to the outside world. Sensitive data must be protected from casual or determined attacks. Lightweight symmetric mechanisms will be used within the network, and SSL/TLS or other

traditional mechanisms used to secure external interfaces. A system of query management centralized at the backbone level in Stargates will authenticate and secure distributed queries and data depending on the dynamic privacy scheme (cf. previous section).

5. **Data fusion**
   In Smart Homes, data fusion is a way to use different techniques based on evidence or probabilistic theories for example, to combine heterogeneous data coming from multi-sensor acquisitions to produce a better estimation of the activity, health status or autonomy. Data fusion is primarily based on data association, and leads to a decision making for alert triggering and medical assistance.

VII. CONCLUSION

The baseline of the system is implemented showing a proof-of-concept. A one week experiment showed a robust system with some straightforward communications from front to back-end. The modularities of this system are numerous and should enable progressive development of the research areas described in Part VI. We believe this system design will greatly enhance quality of life, health, and security for those in assisted-living communities.

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