VISION AND RATIONALE

The U.S. healthcare system is under severe stress and the situation is expected to deteriorate rapidly after 2010, when the first wave of baby boomers reaches retirement age. The Congressional Budget Office predicts "the financing problems in the near term will be dwarfed by the crisis that could occur as the baby-boom generation reaches age 65" [Antos,97]. Today, more than 14% of the GDP is devoted to health care and the yearly increase is about 1/3 of a percent [Smith,98; Levitt,02]. While the U.S. is the leader in healthcare expenditures, it ranks only 37th in overall healthcare system performance [WHO,00]. Reflecting dissatisfaction with the present health care system, US consumers spent $27 billion on health improvement and maintenance (not including diet) outside the established health care system in 1997 [Eisenberg,98]. Soon, aging baby boomers will start to impact health care. Whereas 30 years ago, there were more than 20 able bodied persons for each individual that needed care at home, this ratio will drop to 6 to 1 in 2030 [RWJF,96]. This means that nearly 1 out of 2 households will include someone who needs help performing basic activities of daily living. In summary, our present health care system is expensive and inefficient, consumers are dissatisfied, and the problem, from a demographic and manpower standpoint, will be getting much worse. The personal and economic gain derived from developing a new concept is thus enormous.

Our vision is for a *technology-based engineered system that shifts the emphasis from disease treatment in hospitals to health promotion and quality of life conservation at home*. We will design and build a *Personalized Instrumented Health System* (PIHS) that augments the current health care system with a focus on proactive preventive health. The PIHS will promote healthy lifestyle habits, perform early detection of critical diseases, and provide aids that prolong independent living. The PIHS will achieve these goals by acquiring data, understanding them and transforming them into information, advising individuals, accommodating their needs, and connecting to caregivers or the existing health care infrastructure when appropriate. Abundant evidence supports a health conservation approach as a cost-effective way to keep populations healthy [Chernew,98; Thorpe,97] and financial incentives are emerging that favor preventive care (e.g., capitation and self-insurance), making our approach attractive.

Our approach is to leverage the rapid advances in communications, computing, and sensing technologies to develop a personalized and preventive health care environment based in the home using new technologies that can be purchased by individual consumers, potentially outside the financially-strapped U.S. health care infrastructure. To do so, we must tackle important engineering and research challenges: (1) building hardware and software infrastructure to support distributed sensing capabilities for gathering a wide range of signals and providing storage and retrieval; (2) modeling the captured signals to provide understanding of activity at a single point in time and over some long period of time, and ultimately predict future activity; and (3) actuation of the environment to facilitate communications with and feedback to the individuals and provide timely services in a humane and medically effective way, while respecting privacy.

We propose to focus on a critical but manageable subset of the vast health care problem. Because older Americans are the group most in need of help, we will focus on creating a Personalized Instrumented Health System that facilitates *successful aging*. The PIHS will gather data 24/7 and create a personal health baseline that far exceeds what can be accomplished in hospitals, clinics, and doctor's offices. The PIHS will operate continuously during our daily lives in smart medical homes (2 prototypes are already operational) and with mobile health assistants. It will acquire information through non-invasive sensors to create a total picture of each person's health. It will model and interpret human activity and transform it into formats usable by consumers as well as health care providers, advise the user and caregivers when changes should be addressed, and accommodate to changing abilities by creating adaptive interfaces and adaptive environments. Successful aging requires the promotion of healthy lifestyles, the early detection of disease, and the maintenance and management of chronic conditions. In each case, we have identified health problems on which our team of engineers and health professionals will focus its efforts.

Our decision to focus first on older Americans is thus a deliberate choice. While we do believe that the PIHS will also be useful to working adults and their children (lifestyle choices made early in life can have a large impact later in life), older Americans need these assistive technologies now rather than later. They are the ones for whom the immediate impact of our inventions will be felt and their number is growing fast. Our industrial partners have expressed their support of our decision because commercial products can be developed for this vast market within a few years and also because a growing number of corporations is trying to avoid productivity loss from employees taking care of aging parents. Once tangible positive outcomes are demonstrated, it will be easier to convince the health care establishment, policy makers, and the government to support our approach.

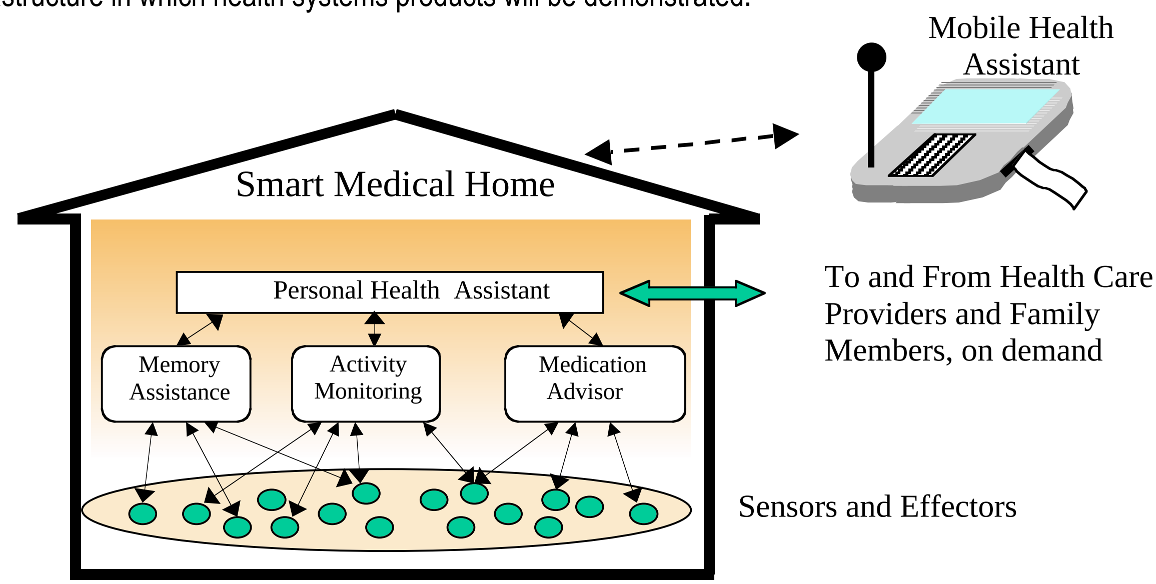
To achieve these goals, we have assembled a very strong multi-university research team uniquely positioned for the proposed Engineering Research Center. Through the ERC program, we will be able to tackle the complex, long-term problems, develop critical test-beds, and approach the issues with a system perspective. Our interdisciplinary team is based at four core institutions (U. Rochester, Georgia Tech., MIT, and U. Florida) and represents many disciplines ranging from engineering and computer science to the sciences, medicine, architecture, and social science. The team represents an alliance involving several groups actively engaged in “health at home” and with a predominant focus on older adults. The core partners all share the vision and bring complementary strengths and foci. The team leadership is well known in their communities and experienced in leading large multidisciplinary research efforts. The faculty participants are diverse and include established leaders, emerging stars, and many award recipients. A strong educational and outreach program has been defined. It includes several joint initiatives involving K-12 and college students, as well as professionals. A prototype of the smart medical home developed for educational purposes will be deployed with the help of the Rochester Museum and Science Center.

STRATEGIC RESEARCH PLAN AND ENGINEERED SYSTEM APPROACH

The strategic research plan and engineered system approach presented here are the result of years of work at our respective institutions, started independently in the second half of the 90s. In 1999, two of our groups, UR and MIT, submitted a pre-proposal to the ERC program, which was invited for a full proposal but eventually declined, in large part because the engineered system approach was not mature. We have since added two core partners, GT and UF. We have refined the vision and identified a clear engineered system focus by performing a top down analysis of the problem, by collecting the input from a large number of health care providers, and by consulting repeatedly with industry and policy makers. In the meantime, UR received very strong financial support from the university, from companies ($0.7M/year) and also secured a $1M grant from the Keck Foundation. GT obtained strong financial support from the Georgia Research Alliance and 3 mid-size NSF ITR grants totaling $4.2M over 5 years. MIT’s effort became a new group at the MIT Media Lab and is receiving strong industrial support. UF expanded its work with a $4.5M Rehabilitation Engineering Research Center on Technology for Successful Aging funded by the National Institute on Disability and Rehabilitation Research. All of us receive financial support from corporations that share our vision. To develop a unified vision, we have held several face-to-face meetings at which the 4 core institutions were represented, organized workshops also attended by others, and visited one another to define themes of common interest and start joint projects. We also have strong professional relationships among the core partners (e.g., past position at another core institution, pre-existing joint projects, serving on another core institution’s advisory board).

What will the Personalized Instrumented Health System do for individuals and society? It will promote healthy decisions by individuals and help diagnose disease early. It will lead to a higher quality of life and a containment of health care costs. Because it will be engineered to function autonomously, it will help solve the projected manpower problem. It will collect data that were never collected before, providing the potential to increase medical knowledge. It will make it possible for people to take better care of themselves. It will create a personal health baseline. How will the PIHS work? It will collect and analyze personal health data 24/7. It will acquire and store longitudinal health data that form a personal health record. It will integrate data from a variety of intelligent sensors and assistive technologies to provide feedback in the right form at the right time and place. It will connect to health care providers, family members, and public health repositories. It will protect privacy. It will help set engineering standards, making the participation of many companies and widespread adoption possible.

We have identified three-test beds where we will test our prototypes, perform experiments involving individuals using and reacting to our devices and systems, integrate the sub-systems to shape the PIHS, and study the relation between the PIHS and the established health care system. The primary test-bed is the *home,* an instrumented living space for health ("health at home"). Two early versions are already operational at UR (the Smart Medical Home) and GT (the Aware Home), and another one is projected to come on line at MIT. The secondary test-beds are an *assisted living community* at Elite Care and a *mobile health assistant* ("health on the road"), led by UF. The facilities at Elite Care will allow us to perform relatively large scale studies by testing our prototypes on many users at the same time. Another important function of these test-beds will be to insure compatibility between the prototypes and develop technology standards across the four institutions. To achieve integration and coordination between the four groups and focus on the systems questions, we will hire senior technical/scientific associates whose primary task will be coordination and integration. The medical system economics and corporate business models for our prototypes will be developed with our corporate affiliates. It is only after all these steps are completed that a product can be brought to market. However, the raison-d'être for the ERC is to define and develop the infrastructure in which health systems products will be demonstrated.



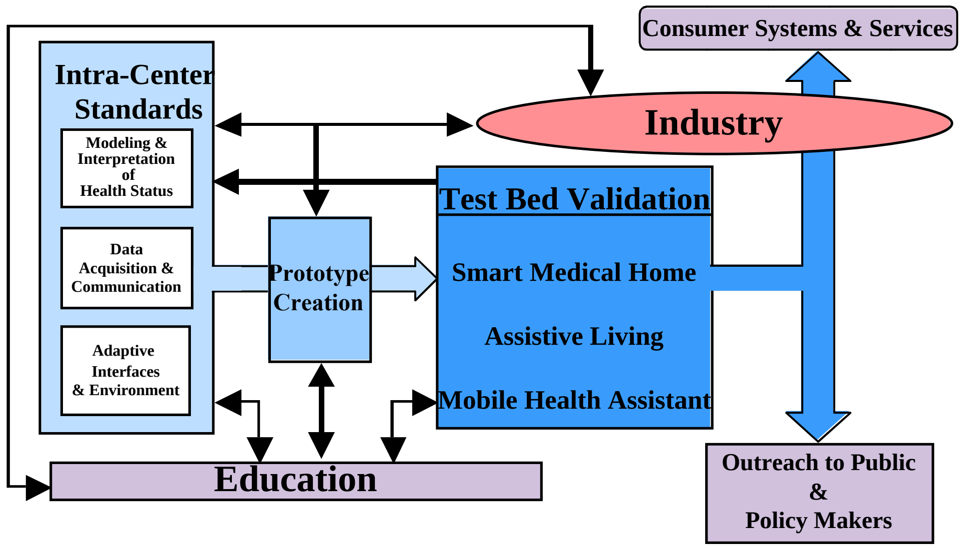
Schematic representation of the Smart Medical Home and the Mobile Health Assistant. Sensors and effectors are combined to perform specific functions (3 of them are shown) which are integrated to produce a personal health assistant. Each sub-system is a module within the entire PIHS.

How does our approach compare to the state of the art? Several of our industrial sponsors conduct work closely aligned with our objectives. Intel, which already supports the UR, GT, and MIT teams, just launched a 3-year Proactive Health Research for Future Elders initiative. Other companies also work in fields that are close to ours. Honeywell's Independent Lifestyle Assistant (ILSA) program, funded in part by NIST, is targeted at developing an intelligent home automation system to enable elderly and infirm users to live and function safely at home. The UF team is scheduled to start testing ILSA in the next 6 months. Corporations like IBM and Microsoft are developing smart home environments outfitted with ubiquitous computing, but their emphasis is not in the area of health.

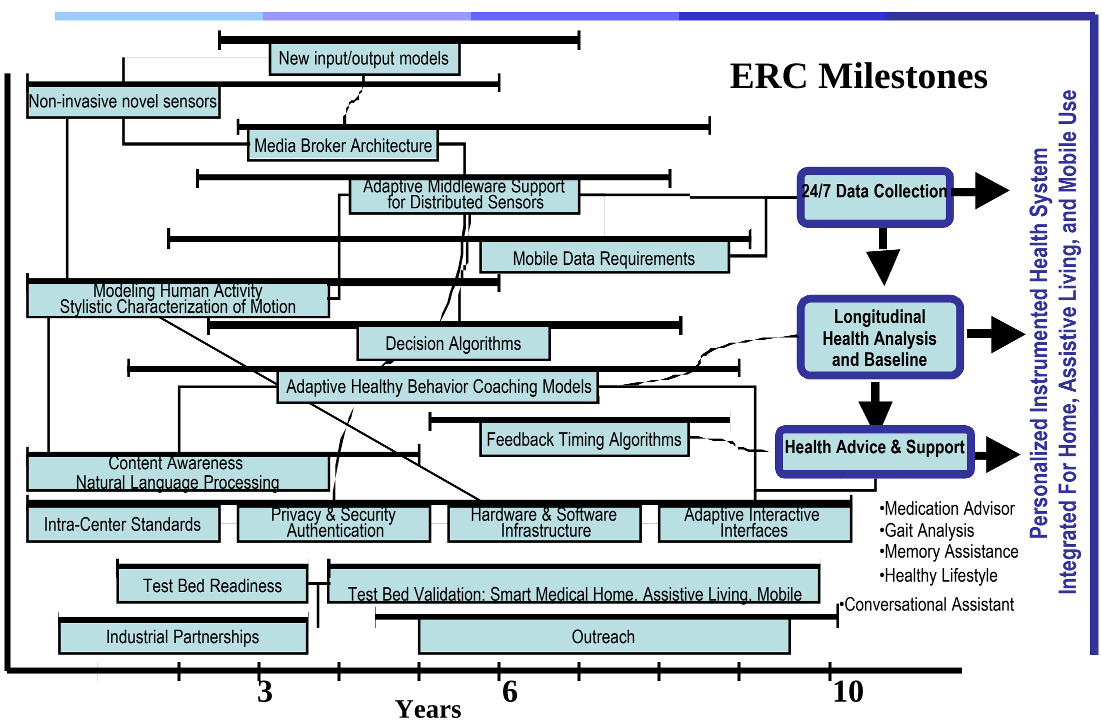
The Georgia Tech Aware Home is one of our two test-beds (the other is the Smart Medical Home at UR) where prototypes are tested and experiments with human subjects have started.

There are many academic centers where engineers and physicians work together. However, the focus is still on the hospital and creating technical solutions to the remediation and cure of disease. Very recently a few academic groups have embraced a focus closer to ours. Among those we have visited, Simon Fraser has a Gerontological Research Center that helps improve the relationship between people and their environment. The University of Toronto has a Center for Global eHealth Innovation with a flexible space that will simulate real world settings where health related information is exchanged. MIT's AgeLab has projects at the intersection of health and technology, but their approach is not an engineered system and they often keep the doctor in the loop. The Veteran Health System has one of the largest home-based technology demonstrations underway in partnership with the UF team. There is also much activity, in industry, the military, and academia, in the telemedicine and telehealth. We view these activities as very valuable and complementary to the proposed ERC: the home of the future will include telemedicine/telehealth capabilities, but this approach does not solve the inescapable demographic and manpower problems that will be encountered. In addition, the US Army Medical Research and Materiel Command – Telemedicine and Advanced Technology Research Center (TATRC) conducts research on the human factors (usability) of telemedicine technologies designed to be used outside traditional medical settings. Faculty from the GT team already act as consultant for this group and we expect to develop fruitful collaborations with TATRC.

Successful aging requires the adoption of healthy lifestyles, the early detection of disease, the maintenance and management of chronic conditions, and aids that enable elders to perform ADLs (bathing, eating) and IADLs (managing a medication regimen, preparing nutritious meals). It may also require their willingness to accept new challenges and to engage in lifelong learning, what we call enhanced activities of daily living (EADLs) [Rogers,98]. These requirements drive the design of the PIHS. From a medical perspective, cardio-vascular disease (CVD) is the number one health problem among elders [CDC,94]. Our approach can help in all aspects of CVD. Prevention can be achieved by promoting physical activity and proper nutrition through reminders provided by a personal health assistant. The onset of the disease can be detected well before symptoms become apparent by analyzing longitudinal health data recorded by a combination of physiological sensors. Early detection of "silent" events such as mini-strokes can be done using gait analysis. Combining smart pill dispensers with an AI system (a medication advisor) can facilitate medication compliance, essential for successful treatment and maintenance of CVD.



Conceptual diagram showing how the test-beds will be used to validate the prototypes created by inter-thrust collaborations and how their results will impact consumers and influence policy makers. The key role of the education programs and of industry throughout the entire Center is illustrated.



Ten-year milestone chart illustrating how progress in the research projects and sub-system deliverables gradually leads to a Personalized Instrumented Health System. The boxes represent key research projects and deliverables. The duration of each of these is estimated by the thick lines above the boxes. The connectivity between the projects and deliverables is shown by the thin lines. The thick horizontal line at the top illustrates the continuous growth and development of the PIHS, by changing into darker shades of blue over time. The test-beds, industrial partnerships and outreach activities are connected to all the projects and deliverables.

These considerations and benchmarking against other centers led us to organize the Center in three technical thrusts that represent measurements, interpretation, and adaptation. Thrust 1 is Data Acquisition and Communication, Thrust 2 is Modeling and Interpretation of Health Status, and Thrust 3 is Adaptive Interfaces and Environment. Research done in Thrust 1 involves biosensors, networking, communications, data base, experience capture, and digital signal processing. In Thrust 2, it is gait analysis, understanding the physical environment, representation, learning, activity recognition (by computer vision or other means), limited intention understanding, and natural languages. In Thrust 3, it is dynamic environment and architecture, modalities to provide information, personalized strategies for healthy behavior, and evaluation.

We will be successful if other groups decide to follow our lead and industry delivers products to the public. We anticipate the research supported by NSF will lead to expanded research programs by the ERC partners sponsored by other agencies such as DOD and NASA. Because the kind of data collected under the ERC program has never before been available to the medical community, we expect that NIH will fund follow-up studies. The resulting medical knowledge will then help ERC researchers develop better systems, thus closing a complete feedback loop from engineering to medicine and back.

RESEARCH THRUSTS

Thrust 1 Data Acquisition and Communication: Leaders: Heinzelman (UR) and Ramachandran (GT) Members: UR: Fauchet, Heppard, Jones, Krauss, Miller, Murphy, Nelson, Rothberg; GT: Abowd, Ahamad, Anderson, MacIntyre; MIT: Intille, Larson, Paradiso; UF: Helal, Melker

PIHS is a living environment in which we can explore technology-based services to support a healthy lifestyle, the early detection of disease, and the maintenance and management of chronic conditions. Such an environment will need to support development and evolution of a range of applications that can then be evaluated for their overall effectiveness and acceptance. The first technological thrust concerns the development of the hardware and software infrastructure to enable the design and deployment of PIHS. These challenges include:

- Development of novel sensing technologies
- New models of input and output that drive the development of applications in ubiquitous computing environments configured for the privacy required of health and medical data
- Middleware support for distributed sensing, including seamless integration of distributed wireless and wired technologies, information security, and abstractions for storage and retrieval of distributed sensed information
- Support for the basic application features of context-awareness and automated capture of information in an instrumented environment
- Mobility: Definition of the type of data that needs to be collected for the Mobile Health Assistant and relation between this assistant and the smart medical home environment.

There are already a large number of commercially available sensors. In many instances (e.g., digital cameras), their capability is increasing while their size and cost decrease. The sensor development research performed at the ERC will focus on physiological and environmental biosensors. We are developing a new family of silicon-based biosensors that have already been used for the rapid detection and identification of tiny amounts of DNA, proteins, and bacteria [Chan,00;01]. Our goal will be to modify and improve these biosensors so that they can be used for personal health outside the laboratory environment. Individuals who may need continuous monitoring of specific physiological signs will wear them. They will be deployed as environmental sensors (e.g., air quality or food safety). The main scientific challenges are sensitivity and robustness (preliminary data are encouraging), whereas the major question for commercialization is the cost.

We plan to develop the system infrastructure for supporting a plethora of sensors and actuators with varying computational capabilities, network connectivities, and bandwidth requirements in an instrumented living setting. The key is enabling simultaneous access to these sensors from different applications while ensuring that the application requirements are not mutually conflicting. We will develop a *media broker* architecture that acts as a clearinghouse for access to sensors and actuators from different applications. Incompatibility of simultaneous access and other manipulation will be handled in the media broker. Further, we will develop high-level application programming interfaces (APIs) that allow *virtualizing* these sensors along different dimensions for easing the application burden. For e.g. an application may want to be informed when the activity in a bedroom where an elder is resting goes above a certain threshold. A useful side benefit of virtualizing sensors is that failures can be handled seamlessly at the application level. For example, an application may not care which specific optical sensor such as a camera is providing input from a particular location (assuming there are multiple cameras for that location). Thus upon failure, the media broker can switch over to another physical sensor with the same coverage without any perturbation at the application level.

Often it may be necessary to *fuse* inputs from several sensors to create a composite hypothesis (e.g. camera and audio inputs). We will develop high level API that provides a variety of sensor fusion options at the application level. *Time* is an important attribute when dealing with sensor data. Most programming systems offer no handle on time at the application level. D-Stampede [Adhikari,02; Ramachandran,99] is a distributed programming system that provides high level APIs for indexing data streams temporally, correlating different data streams temporally, performing automatic distributed garbage collection of unnecessary stream data, supporting high performance by exploiting hardware parallelism where available, supporting platform and language heterogeneity, and dealing with application level dynamism. This system will serve as a base for developing the sensor fusion mechanisms as well as the media broker architecture. These system mechanisms will be developed as instances of *aspect-oriented programming* support on top of D-Stampede to reduce the programming burden at the application level.

An instrumented living environment will collect much information concerning the whereabouts and activities of individual residents. While we promote the services this can provide to an aging population, we cannot and will not ignore the social implications. Privacy and security can be technical, as well as social, challenges. We will push on technological solutions or mechanisms for supporting privacy and security values in this research. One approach is to create "opt-in" systems that, beyond giving a base level of utility, allow the user to weigh the potential benefits of participating versus the amount and type of information revealed [Lyons,00; Starner,97]. In addition, we wish to create physical artifacts, which are associated intuitively with the aggregation of information about the user. A logical extension to this “opt in” policy is to adopt the model that all information regarding an individual within the PIHS is stored within the walls of the smart medical home. Any request for this information that is to be delivered to an agent outside the house must be approved for distribution by the resident first. Authentication is a security research challenge that should be facilitated in middleware, such as the Context Toolkit developed by us [Dey,01]. One advantage that the Context Toolkit provides is the direct ability to attach ownership to sensed data at the time of acquisition, through the context widget, and to automatically retain that ownership through to a request for the information. At request time, novel authentication rules can be enforced based on the person requesting the information (subject-based roles), the entity for which information is requested (object-based roles), or the situation in which the information is being requested (environmental-based roles) [Covington,01].

The key to the effectiveness of the PIHS is enabling seamless coordination among the low level devices to accomplish the high level application tasks with a required reliability and a minimum cost. Our task is to develop a generic middleware that presents applications with an interface to specify their low level data needs (e.g., sensor input), how they vary over time, and how each application's performance is affected with varying sets of input data. Knowing this information will allow the middleware to manipulate the network configuration, taking into account the tradeoffs between application performance, data availability, and energy consumption.

We will build a middleware system that controls the network configuration based on application performance/network cost tradeoffs. It is essential to have such a middleware system to allow applications to easily be built on top of dynamic sets of sensors. The middleware will allow multiple applications to co-exist in the same space without interacting negatively. Among the anticipated roadblocks is the fact that current middleware systems do not affect the network configuration. There are some middleware systems that inform the application about changes in the network so the application can adapt, but there are no middleware systems, to our knowledge, that adapt the network based on application requirements.

Applications built for dynamic distributed systems are built to operate using differing sets of low-level components, where the components may change over time. For example, sensor network applications that are required in a health-monitoring environment function using different numbers of sensors (e.g., temperature, blood pressure, etc.) as input. The effect of using differing sets of sensors is a change in the performance of the application as well as a change in the cost associated with getting the data to the application. We propose designing a middleware that configures the network (e.g., determines which sensors to network together and how much data bandwidth to allocate to each sensor) by determining the best tradeoff of application performance versus cost. To accomplish these goals, the middleware will

- accept input from the application concerning its overall performance using different sets of sensors in different situations (e.g., in emergency vs. stable situations)
- collect network characteristics including available components and cost to transmit data
- make network configuration decisions to balance application performance with cost over time

It is important that the essential features of the PIHS be maintained outside the home environment. Emerging mobile devices such as wearable computers and “smart phones” are poised to give a new dimension to the way we perform our daily activities [Helal,99]. We have recently shown that smart phones allow elders to interact with, monitor and control their surroundings, and in another demonstration, we have shown that they can provide reminders to take medications, assurances that the elder has taken the correct medication, and automatic drug refill and delivery at home [Mann,02]. The mobile health assistant will greatly expand upon these early demonstrations to become an essential part of our health continuum. It will augment health at home with health away from the home by using wireless and mobile technologies. However, the mobile health assistant cannot provide the same palette of functionalities as the home and thus choices must be made on what it does and how it is connected to the home. These choices are driven in part by technology, in part by economics. Among the most interesting questions are the development of software components capable of handling the weak connection to and the disconnection from the home, including synchronization and adaptation.

Thrust 2 Modeling and Interpretation of Health Status: Leaders: Allen (UR) and Essa (GT)
Members: UR: Berg, Ferguson, Nelson, Papier, Tekalp, Utell; GT: Bobick, Dellaert, Rehg, Starner; MIT: Intille, Paradiso, Pentland, Picard

The second technological thrust focuses on the automated characterization, recognition, and interpretation of human health status in instrumented environments. The goal of this research is to convert the sensory data provided by the infrastructure described above (thrust 1) into information used to guide feedback and/or provide intervention by the PIHS (thrust 3). The ability to interpret what is happening at any single point in time and over some period of time, and ultimately to predict future activity is a crucial for the PIHS. An effective PIHS will rely on the following very high-level of information to achieve its goal of supporting everyday activities:

- Make intelligent decisions regarding data organization, compression, and indexing such that storing and searching longitudinal health information does not become intractable and maintains its medical utility, and an individual health record is produced.
- Develop patterns of routine activities and determine variations from such activities, as these are primary indicators for deviation from normalcy, resulting in a structural anomaly of activities, which could be an indicator of severe health problems. (ADLs mentioned earlier can help with this for the elderly).
- Recognize complex, subtle physical or psychological patterns (e.g. early signs of mini-stroke, Alzheimer's, or clinical depressions) by analysis and fusion of all sensory data available, over short-term and long-term.
- Provide abilities for natural language interaction with the environment to allow for queries about activities in the home (e.g., "did I actually take that medication?" to "where did I leave my glasses?")

The instrumented living environment provides with us with 24/7 data streams from various sensors. Cameras (optical sensors) are very well suited for the measurement of physical and motor activities. Motor movements are considered highly diagnostic of a variety of health parameters and therefore worth characterization and monitoring by PIHS. We have developed several techniques [Bobick,01] for the *recognition of basic motor control activities* (such as sitting down or walking). However, recognizing the basic activity is not sufficient. Rather, the system must assess certain stylistic or systematic parameters of the execution. For example, does the person rise from a chair with more difficulty than observed in recent weeks or months? This "stylistic" characterization of motion is just now becoming a deep concern in computer vision, the computer perception of motion [Tunawongsuwan,01;Brand,99] and fundamental progress in this area is required for the effort here. We propose to build on top of our own work for tracking, representing and recognizing human movements to get towards such stylistic characterization of movements [DiFranco,01;Dockstader,01]. We are specifically interested in building a detailed representation of such activities by learning from motion studies and building multi-view vision-based motion capture systems [O'Brien,00;Tunawongsuwan,01;Brostow,99] to aid in tracking and recognition stylistic and longer-term variation in such physical activities.

A special case of physical assessment is *gait characterization*. Gait is an important specific physical activity because not only does a change in gait predict possible changes in mobility and mobility requirements, it is also being investigated as a diagnostic tool for the early detection of the onset of a variety of neuropsychological conditions such as stroke and Alzheimer's [Craik,95]. Our previous work on gait characterization and recognition [Bobick,01;Johnson,02;Dockstader,01] addressed variations between individuals, i.e., focused on signature elements that could be extracted from gait and exploited for recognition. For this proposal we shift our attention to within-individual gait variation. In particular, we will generate characterizations that reflect general mobility capabilities (such as speed or steadiness) as well as specific properties indicative of potential serious conditions.

An equally important part of the PIHS is the *monitoring of complex activities* within the environment and categorization of such activities with respect to previously modeled actions. We have already reported on our work on using object-context relationships [Moore,99] and context-free grammars [Moore,02;Ivanov,00] to recognize complex activities in environments. We are now working on extending these to deal with various forms of ADLs and other routine everyday tasks, each with varying level of temporal variations. These include activeness measure while watching television to cooking to monitoring a regiment of medication and other health milestones requiring specific measurement. A large part of this work requires building detailed primitives of actions that can be observed and then linking these within a structure of various activities.

Integration of object recognition, activity recognition, and natural language processing is also an important aspect of the PIHS. Following our work on object recognition [Selinger,01] and combining object and action recognition [Moore,99], we develop an integrated system to support recognition of both objects and the related activities in the space. This approach will be further augmented with a natural language interface to support queries about activities in the home. In addition, an integration between spoken language systems and activity monitoring system will also be researched so as to allow for temporal reasoning based on information that is gleaned from a spoken language recognizer. For example, one sensor identifies the person that just entered the kitchen, and we infer, based on knowledge from a conversation earlier, that they are going to make coffee). Such integration at the context level can provide for high-level reasoning and even prediction of expected events and lack of compliance in such cases (e.g., "said that they were going to take some medication, but forgot when they got to the medicine cabinet"). Such an interpretation of conversations requires the building of spoken language understanding systems that can identify meaning from speech, compensate for speech recognition errors, improve the language models that drive speech recognition, build highly efficient natural language parsers that can compute meaning from words, develop broad coverage grammars of spoken language (in contrast to grammars of written language which have been more thoroughly studied), develop a meaning representation language that is useful for subsequent reasoning, and develop models of multi-modal interfaces (i.e., that combine graphics and speech effectively).

This form of interaction between spoken language interpretation and action recognition can aid in developing the technology required to identify the person's intentions from what they said, to identify the motivations that are only implicit from the interaction (e.g., inferring someone has a headache even if they don't say so), to fill in what is implicit in the utterances from the context (both the discourse context based on what has been said previously, and the environmental context from monitoring in the home), and to determine the best way to interact in order to maintain a helpful interaction.

Finally, such high-level monitoring of all forms of multimodal sensory data for extended periods can also provide extensive cues toward the state of the resident (again, at a specific time and over extended periods) [Picard,97]. This includes a handle on the emotional state of the user, as can be measured by audio quality measurements [Gardner,98;Fernandez,00]. Implementation is possible using the various phased array microphone systems being installed for spoken language interaction between the user and the environment. We have also done considerable work on expression and emotion recognition from faces [Essa,97;Reveret,01], however, such recognition requires very high-resolution dynamic imagery of faces. The high-end data-parallel infrastructure as provided by D-Stampede will help with the processing to support our algorithms aimed at tracking faces in real-time. We propose to undertake some initial studies in this area in the first five-year phase of this effort, with more emphasis on this direction in the later years.

Thrust 3 Adaptive Interfaces and Environment Leaders: Dye (UR), Rogers (GT), Intille (MIT), Mann (UF) Members: UR: Allen, Cushman, Dozier, McIntosh, Ossip-Klein, Scherer; GT: Abowd, Mynatt; MIT: Larson, Pentland, Picard; UF: Marsiske; FHCRC: Bowen; Elite Care: Lundberg, Reed

In this thrust, social scientists, engineers, AI specialists, and health care practitioners investigate how appropriate feedback can be given to individuals and personalized strategies for healthy behavior can be developed (unsafe lifestyle practices account for 46% of premature deaths in the U.S. [CDCP,94]). Effectively, they ensure that the assistive technologies developed for the PIHS act together as a personal health assistant that helps elders manage complex situations and make healthy choices. Key questions include how to interact with the individuals (language, graphics, messages), when to interact with them (what are the teachable moments) and how to insure that they have taken the appropriate action (e.g., has the pill actually been taken?). The researchers also evaluate and validate the various sub-systems deployed in the test-beds using healthy elders or elders with specific health problems. They also perform field studies to understand better the needs of specific populations and they help develop guidelines that satisfy ethical and privacy concerns.

12-17% of acute hospital admissions for patients over age 70 have been attributed to adverse drug reactions whereby the individual took the wrong medication, too much of a medication, or medications that had adverse interactions (they take an average of 7 prescription medicines and 3 over-the-counter drugs [Fleming,93]). Thus a reminder system that improves medication adherence and provides information about drug interactions is highly desirable. Research in the area of medication management for older individuals suggests that reminders can enhance the safety and effectiveness of medications [Park,97; Morrow,96]. We have just completed the development of a very simple AI system that talks and uses natural language to help individuals manage a simple medication regimen. However, how to provide reminders, engage in a dialog with the user, and verify compliance for a complex medication regimen in a robust manner using an autonomous system is a critical research question. We will assess the role of the complexity of the instructions, the number of medications, the degree to which the regimen is changing frequently, and the potential benefit of an environmental support such as optional message repetition. A long-term goal is to integrate this medication advisor with physiological sensors and smart pill boxes.

Older adults vary tremendously in terms of their functional abilities. Therefore, we will design interactive technology that adapts to users' needs and not merely respond to commands. Emerging technologies can provide the opportunity to "construct technology that can augment greatly the adaptivity and functionality of the older adult user" [NRC,00]. Success in the development of adaptive and interactive interfaces will depend on a solid understanding of the underlying behavior of individuals in their environments. Critical is that the components of the engineered system (1) do not stigmatize the users, (2) can be easily retrofit into existing homes, and (3) provide a real, lasting perceived value to the occupants so that the technology remains continuously active. Two key problems that will be studied are using the system to provide memory supports and using the system to provide context-aware educational messaging to motivate long-term healthy behavior.

Memory Supports: Forgetting things can influence safety, health, well-being or quality of life (turning off the stove, taking medication, locking the front door, and leaving the bath water running). These examples represent the two types of memory problems experienced by older adults: retrospective memory (remembering the past- what was I doing?) and prospective memory (remembering to do something at a specific time - taking a medication at 3:00 PM). Although smart environment technology offers great promise of helping elders compensate for both types of memory deficits, understanding the nature of and delivering the feedback and the relationship between memory and the environment are critical to the development of new technologies. This information is crucial for the development of new user interfaces that will enable the reduction of the cognitive burden of doing everyday activities essential to independent living. We will first focus on support for sequential tasks, such as those involving medical devices [Rogers,01].

Motivating healthy behavior: Field interviews with medical professionals, educators, and homeowners have led some of us to the conclusion that the goal of homes of the future should not primarily be the simplification or elimination of everyday tasks in the home. In fact, task simplification may be in direct conflict with the goals of encouraging healthy lifestyles, physical exercise, and mental well-being. Medical professionals suggest that developing systems that *require* human effort in ways that keep life as mentally and physically challenging as possible as people age should be the goal. Although in some instances we may want to use automation to allow people to accomplish tasks they can no longer perform on their own because of a disability or frailty, our primary vision is not one where computer technology is ubiquitously and proactively managing the details of the home. We will develop components that allow the PIHS to be used to motivate healthy behavior using context-aware sensing. Although there is skepticism that a computer system might motivate people to change their behavior, researchers in a variety of non-IT fields have convincingly demonstrated the power of point-of-decision messaging to motivate behavior change [Komaki,78; Guastello,93; Geller,84]. So far, the systems only work for some of the people some of the time, although studies have consistently shown that context-sensitive information presentation can make a difference (e.g. doubling the number of people who take stairs in public spaces [Brownell,80].

Extremely simple messages presented at the right moment can and do influence behavior. Thrust three researchers will explore how non-intrusive, ``just-in-time'' messaging can be conveyed as people are in environments for motivating healthy behavior [Intille,02a]. Also to be developed are tools that use the sensing technology of the PIHS to measure how effective such messages might be [Intille,02b]. We are interested in three points in time: the point of decision, the point of behavior, and point of consequence [Fogg,00]. Thrust 3 researchers will work with the sensors developed by the remainder of the ERC team in order to develop user interfaces that automatically detect and then exploit specific (and sometimes fleeting) points of decision, behavior, and consequence. The goal is to develop strategies for the design of human-computer interfaces for the elderly that help people learn how to take control of their long-term healthcare. We will focus on nutrition and exercise, the two top high-priority areas to improve health in the U.S. [USDHHS,00]. We envision a system that first makes current nutritional information more accessible to older adults and then tracks activity, nutritional needs, and food intake. Such a "nutrition coach" will assist older adults to eat healthfully. Cognitive functions have been shown to improve after a six-month aerobic exercise program [Kramer,01]. Thus, our goal will be to provide support for exercise through monitoring, tracking (such as done in Thrust 2), feedback, and information.

Thrust 3 researchers will work to integrate the sensing tools developed in the other thrusts so that a system of sensors and computer intefaces can be easily deployed in environments to fulfill fundamental needs of the aging population. It is critical to do this in a way that does not stigmatize the population and, whenever possible, leads to tools that are as useful for the healthy as they are for the chronically sick. Efforts will be made to measure the impact of point of decision messaging delivered via user interfaces developed for two different platforms: portable computing devices such as PDA/cellular phone hybrids and future home environments with easy-to-retrofit "augmented reality" and ubiquitous display technology [Pinhanez,01]. Either of these methods can make it easy to present information at the *right place*. The challenge then becomes to develop algorithms that can recognize the right time and select a presentation strategy suitable for the given context. The thrust 3 researchers will work with the leaders of the other thrusts to ensure the sensing and user interface components of the PIHS can be retrofit into existing homes and used in studies to evaluate the effectiveness with which computer systems can actually impact health-related behavior in real home environments. Interface prototype will be developed using participatory design techniques that involve the target elderly community early in the design process.

EDUCATION AND OUTREACH PROGRAM

The fundamental educational missions of the Center are to train engineering and also medical professionals who can develop and implement novel technology that improves the health of individuals, and to increase public awareness about the potential of technology for personal health. The specific training objectives are three-fold. First, expand the educational background of engineers and scientists to include the ethical, societal and economic issues related to implementation of health care technology in the community. Second, educate health care and social scientists about the capabilities and limitations of novel health care technology. Third, increase public awareness of the benefits of personal health technology, by bringing information and educational materials into public education and community institutions. The student populations to be served include undergraduate, masters and doctoral students at the 4 core institutions plus our academic outreach partners (presently Hutchinson Cancer Center and we expect Morehouse College in the fall). We have agreed to dramatically increase our interactions through summer fellowships for students from minority institutions; we are also committed to creating and funding a sabbatical program for their faculty members. Our plans call for an increase in the number of our educational outreach partners to include other underrepresented groups in engineering and science, such as students from women's colleges.

A wide array of educational experiences will be offered over a 5-year period. The budget requested from the NSF ERC program for the Education and Outreach program will barely allow us to start some of these. We are fully committed to aggressively pursue all funding sources, federal and private, to support this key program, such as our already funded and pending training grants from NIH.

Community Outreach: We will develop a Smart Medical Home interactive exhibit that can be used for outreach activities, will provide "hands-on" opportunities and will continue to evolve throughout the lifetime of the Center. It will be used as a traveling exhibit. We will explore opportunities to display a scaled-down exhibit at schools. An interactive Web site will also provide public education. This project will be developed starting in year 2, with one of our Outreach partners, the Rochester Museum and Science Center, playing the lead role. We expect that other museums will join us in the near future.

K-12 Students and Teachers: Several programs will be implemented to provide education and training for secondary school students and their teachers. Our outreach programs will include both individual research activities for students and teachers during the summer months and team projects carried out by a group of students with a teacher during the school year. Such programs, which are already available in an embryonic form at several of the core institutions, will be integrated and expanded across the core institutions. Fellowships will be offered to fund teachers for a 4-week hands-on research experience in the Center. During the summer program, weekly seminars and lectures will be held covering the technical and scientific underpinnings of center projects. During the academic year, the teachers will attend a monthly advanced seminar series that will explore issues associated with Center research. These seminars will be eligible for continuing education credits for practicing teachers. During the school year, those teachers who participated in the program will be expected to work on a research project with a group of students at their school and work in collaboration with one of the Center's members. Much of this research activity will take place by communicating over the Internet.

In parallel with the program for teachers, selected high school students will be invited to work on research projects for eight weeks during the summer. Under-represented minority students will continue their experience in a mentoring program in which they spend one afternoon per month shadowing a faculty member or graduate student in the center and continuing their research project. At the end of the academic year, students will give a short presentation describing their research. From the enthusiastic reaction of young people when they hear some of the Center's goals and projects, we expect that many will come back to engineering because of the perceived relevance of our work.

Undergraduate Research/Internship Opportunities: The Center will provide a rich and diverse array of research opportunities for undergraduates. The Center will help faculty in the associated departments to create projects and design opportunities for the students as part of their undergraduate curriculum. The Center's Associate Director for Education and Outreach will be responsible for identifying specific undergraduate research opportunities, publicizing them, and finding matches at the core institutions for their abilities and interests. For example, at UR, all undergraduate students in Biomedical Engineering already engage in design projects within the context of projects ongoing in the Center.

In addition to research associated directly with undergraduate degree programs, the Center will provide opportunities for both engineering and social science students from all core and outreach institutions to engage in summer research projects. Students from an educational network of two-year and four-year colleges will be invited to join a research effort during the summer, including through the Research Experience for Undergraduates (REU) program. These mechanisms will develop a pool of qualified and interested students who are likely to apply to graduate programs involved with the Center. In developing these opportunities for underrepresented groups, we will work with the existing McNair Program at the University of Rochester to expand the number and types of summer research opportunities already being offered. A formal 10 week program will be organized that will include weekly seminars and special topics lectures, culminating in a one day scientific meeting at which students will present the results of their research. The Center will assist in providing opportunities for undergraduates to engage in industrial internships with companies associated with the Center. The Center will identify internship opportunities and to recruit qualified undergraduates to participate in the internship program. This will provide companies with a valuable inside track in identifying young talent, and it will provide students with an important broadening of their educational experience as well as the opportunity to identify and evaluate potential future employers.

Training in Public Health Technology and Systems: Coursework is being developed to educate engineers about practical aspects of health care delivery. It will provide in-depth training in ethical and societal issues related to implementing novel health care technology. Medical and social science students will be educated about recent technological advances that can have a major impact for improving the quality and delivery of health care at a personal level. These courses will be aimed at beginning graduate students or upper level undergraduates from very different disciplines. The courses will be made of 1/3 semester-long modules and will be open to our industrial partners. Initial plans call for the implementation of three courses, Introduction to Health Technology, Medical Informatics, and Health Technology in the Community. Team-taught courses focusing on the systems-level requirements of personalized instrumented health systems will be developed. Ethical and privacy issues will be prominently featured.

For engineering students in particular, an important part of their educational experience will be a required internship with one of our industrial partners for a minimum of one semester. The exchange of students with industry will educate students about industrial concerns, system concepts, and manufacturing principles, and it will also energize industry-academia collaborations and give industrial partners opportunities to identify talented individuals and play a role in their education and career development.

Continuing Education: A distinguishing goal of the Center is to train physicians and other health care providers in the benefits and uses of technological innovations. Post-doctoral research fellowships will be offered to support physicians interested in the implementation of novel technologies in a community setting. Continuing education modules will be developed and made available to health care providers.

INDUSTRIAL COLLABORATIONS AND TECHNOLOGY TRANSFER

Industrial collaboration does not start when a demo is successful and a prototype is under design, but as early as at when a new concept is created. The UR, GT, MIT, and UF groups presently have three successful but different models for industrial collaborations, support, and technology transfer. The proposed conditions and benefits of membership in the ERC industrial consortium will be summarized in the full proposal. They will be uniform across the four core partners, administered from the Center for Future Health, and use the Center for Future Health model (for details, see http://www.futurehealth.rochester.edu) – different membership levels with sliding fees, multiyear agreements, specific intellectual property agreements, members from very different sectors of industry, focus on collaborative research and on using the Center as a neutral meeting ground where joint projects and standards can be agreed upon, possibility of having industrial scientists spend extended periods of time at the Center.

Several mechanisms will be put in place to facilitate technology transfer. The Center will provide funds to support sabbatical leaves by faculty at industrial partners and by industry scientists at the Center. All Ph.D. students will be required to spend an internship at an industrial partner. Other industrial benefits include membership in the Scientific and Industrial Advisory Board, yearly visits by faculty members to each industrial participant, participation in the closed part of the Annual retreat, special briefings and internal seminars, weekly forums available by teleconferencing, and modular short courses.

MANAGEMENT AND INFRASTRUCTURE

The Center management includes the directors and thrusts leaders, a Scientific and Industrial Advisory Board (SIAB), and a Dean's Council. The Center's Executive Committee includes the Director, one Associate Director at each core partner institution, a Medical Director, an Associate Director for Education and Outreach, an Associate Director for Industry Liaison, and the Thrusts Leaders. The Center Director, Prof. Fauchet, is responsible for integrated operation of the Center. In consultation with the other directors and with the Dean's Council, he is responsible for all personnel decisions regarding the Center, including faculty participation. He reports to UR's Dean of Engineering and the SIAB. He is the founder of the Center for Future Health and has a successful, track record of creating and managing complex research initiatives. Presently, he is the chair of the ECE department, a position he will relinquish at the start of the ERC. The Associate Directors are Profs. Abowd (GT), Larson (MIT), and Helal (UF). They advise the Director in all the strategic and scientific missions of the Center, work with him for allocation of funds and resources, are responsible for their institution's effort, and bring the diversity of backgrounds required for this proposal. They have an established track record of directing major research initiatives in their respective institutions. The Medical Director, Prof. Pentland, M.D., advises the Director and coordinates the work of the clinicians. She is the co-founder of the Center for Future Health and has major responsibilities at the UR Medical School, including Chair of Dermatology. The Associate Director for Education and Outreach is Prof. Mottley. Presently, he is the Associate Dean for Undergraduate programs at UR, a position that he will relinquish at the start of the ERC. The Associate Director for Industry Liaison is Ms. Horwitz, M.B.A. She has the same position at the Center for Future Health and more than 20 years of experience in industry. The Thrust Leaders are for, Thrust 1, Wendi Heinzelman and Umakishore Ramachandran, for Thrust 2, James Allen and Irfan Essa, and for Thrust 3, Timothy Dye, Wendy Rogers, Stephen Intille and William Mann. They develop and coordinate the specific research projects in their thrust and work closely with the Center Directors. The Directors will meet monthly via (video) conference calls and tri-annually face-to-face. The Executive Committee will meet as a whole twice a year. An annual Center retreat will be held; it will have a public and a closed part.

The Center will also have an Administrative Director (responsible for management and administration), one scientist/engineer (responsible for coordinating the joint projects and developing common standards) at each of the 4 core partners, a student leadership council that will work with the Associate Director for Education and Outreach, and a Dean's Council as mandated by NSF. The Scientific and Industrial Advisory Board meets tri-annually to ensure that the research goals are being met and that all the other deliverables are provided. It is chaired by an industrialist and is composed of the Center's industrial sponsors and key leaders not formally affiliated with the Center. Among those who have agreed to serve from the start is Eric Dishman from Intel. A Strategic Planning Advisory Board, composed of front-line health care providers, policy makers, consumer organizations, and community and industry organizations, will guide the Center in the selection of the appropriate health technologies and systems. Such a group is successfully in operation at the Center for Future Health and it will be enlarged to advise the ERC.

REFERENCES

Centers for Disease Control and Prevention, 1994. “Ten leading causes of death in the United States,” 1990 (Atlanta, US Dept of Health and Human Services).

National Research Council, 2000. “The aging mind: Opportunities in cognitive research,” Washington, DC: National Academy Press.

Robert Wood Johnson Foundation, 1996. “Chronic Care in America: A 21st Century Challenge,” Eatontown, NJ.

US Department of Health and Human Services, 2000. “Healthy people 2010: understanding and improving health,” (Washington DC, US Government Printing Office)

World Health Organization, 2000. “The world health care report – health systems: improving performance,” (Geneva, World Health Organization)

Adhikari, S. Arnab Paul, and U. Ramachandran, 2002. ”D-Stampede: Distributed Programming System for Ubiquitous Computing,” To Appear in 22nd International Conference on Distributed Computing Systems (ICDCS)},Vienna, Austria, July, 2002.

Antos, J.R., 1997. CBO Testimony: 2010 and Beyond: Preparing Medicare for the Baby Boomer, U.S. Congressional Budget Office Testimony, August 1997. http://www.cbo.gov/showdoc.cfm?index=308&sequence=0&from=5

Bobick, A. and Johnson, 2001. "Gait recognition using static activity-specific parameters" in Proceedings of Computer Vision and Pattern Recognition Conference (CVPR 2001), Kauai, Hawaii, December 2001.

Bobick, A. and Davis, J., 2001. “The recognition of human movement using temporal templates,” IEEE Trans. Pattern Analysis & Machine Intelligence.

Brand, M. and Hertzmann, A., 2000. "Style Machines", in Proceedings of ACM SIGGRAPH 2000.

Brostow, G., and I. Essa, 1999. "Motion-based Video Decompositing," in Proceedings of IEEE International Conference on Computer Vision 1999 (ICCV'99), Corfu, Greece, March 1999.

Brownell, K.D. and A.J. Stunkard and J.M. Albaum, 2000. “Evaluation and modification of exercise patterns in the natural environment”, American Journal of Psychiatry 137, pp. 1540-5.

Chan, S., Fauchet, P.M., Li, Y., Rothberg, L.J., and Miller, B.L., 2000. “Porous Silicon Microcavities For Biosensing Applications,” S. Chan, , Phys. Stat. Sol. (a) 182, 541-546.

Chan, S., Horner, S.R., Fauchet, P.M., and Miller, B.L., 2001. “Identification Of Gram Negative Bacteria Using Nanoscale Silicon Microcavities,” J. Am. Chem. Soc. 123, 11797-11798.

Chernew, M.E., et al., 1998. “Managed care, managed technology, and health care cost growth: A review of the evidence,” Medical Care Research & Review 55, 259-288.

Coen, R.J., 2001. Bob Coen's Insider's Report. Internet, December, 2001. Http://www.mccann.com/insight/bobcoen.html.

Covington, M.J., Long, W. Srinivasan, S. Dey, A.K., Ahamad, M., and Abowd, G.D. 2001 “Securing context-aware applications using environment roles,” In Proceedings of the 6th ACM Symposium on Access Control Models and Technologies (SACMAT 2001), May 3-4.

Craik, R.L., and Oatis, C.A., 1995. “Gait Analysis: Theory and Application,” Mosby-Year Book; ISBN: 0801669642; 1st edition (January 15, 1995)

Dey, A.K., Salber, D. and Abowd, G.D. 2001 “A Conceptual Framework and a Toolkit for Supporting the Rapid Prototyping of Context-aware Applications,” Human-Computer Interaction Journal. Anchor article for special issue on context-aware computing. Vol. 16, Numbers 2-4.

DiFranco, D., Cham, T.-J., and Rehg, J.M., 2001. “Reconstruction of 3-D Figure Motion from 2-D Correspondences,” in Proceedings of Conference on Computer Vision and Pattern Recognition, Kauai, Hawaii, December 2001.

Dockstader, S.L., and Tekalp, A.M., 2001. "Multiple Camera Tracking of Interacting and Occluded Human Motion," Proceedings of the IEEE (Invited / Special Issue), vol. 89, no. 10, pp. 1441-1455, October 2001.

Eisenberg, D.M., et al., 1998. “Trends in alternative medicine use in the United States, 1990-1997: results of a follow-up national survey,” Journ. American Medical Assoc. 280, 1569-1575.

Essa, I. and Pentland, A, 1997. “Coding, analysis, interpretation, and recognition of facial expressions,” IEEE Trans. Pattern Analysis % Machine Intelligence 19, IEEE Computer Society Press, July 1997.

Fernandez, R. and Picard, R.W., 2000. "Modeling Drivers' Speech under Stress", ISCA Workshop on Speech and Emotions, Belfast, July 2000.

Fleming, B.B., Pulliam, C.C., Perfetto, E.M., Hanlon, J.T., & Bowling, J.M., 1993. “Medication use by home health patients”, Journal of Geriatric Drug Therapy, 7, 33-45.

Fogg, B.J., 2000. “Persuasive Technologies and Netsmart Devices. In Information Appliances and Beyond”, ed. E. Bergman, Morgan Kaufmann Publishers.

Gardner, A. and Essa. I., 1997. "Prosody Analysis for Speaker Affect Determination", Appears, Proceedings of Perceptual User Interfaces Workshop (In Conjunction with UIST 1997 Conference), Banff, Canada, October

1997.Geller, E.S. 1984. “ A delayed reward strategy for large-scale motivation of safety belt use: a test of long-term impact”, Accid. Anal. and Prev. 16, pp 457-463.

Guastello, S.J., 1993. “Do we really know how well our occupational accident prevention rograms work?”, Safety Science 16, pp 445-463.

Helal, A. et al., 1999. “Any time, anywhere computing: Mobile computing concepts and technology” (Kluwer Academic Publishing)

Intille, S.S. and K. Larson, and C. Kukla, 2002a. “Just-In-Time Context-Sensitive Questioning for Preventative Health Care,” Proceedings of the AAAI 2002 Workshop on Automation as Caregiver: The Role of Intelligent Technology in Elder Care, July, 2002. (to appear)

Intille, S.S. and C. Kukla, and X. Ma, 2002b. “Eliciting User Preferences Using Image-Based Experience Sampling and Reflection”, Proceedings of the Conference on Human Factors and Computing Systems, April 2002.

Ivanov, Y.A. and Bobick, A.F., 2000. “Recognition of Visual Activities and Interactions by Stochastic Parsing,” Transactions on Pattern Analysis and Machine Intelligence 22(8), 852-872 (2000)Raul Fernandez and Rosalind W. Picard (2000), "Modeling Drivers' Speech under Stress", ISCA Workshop on Speech and Emotions, Belfast, July 2000.

Johnson and Bobick, A., 2001. "A Multi-view Method for Gait Recognition Using Static Body Parameters" in 3rd International Conference on Audio- and Video Based Biometric Person Authentication, pages 301-311, Halmstad, Sweden, June 2001.

Komaki, J. and K.D. Barwick and L.R. Scott, 1978. “ A behavioral approach to occupational safety: pinpointing and reinforcing safe performance in a food manufacturing plant”, J. Appl. Psychol. 63, pp 434-445.

Kramer, A. F., Hahn, S., McAuley, E., Cohen, N. J., Banich, M. T., Harrison, C., Chason, J., Boileau, R. A., Bardell, L., Colcombe, A., and Vakil, E., 2001. “Exercise, Aging, and Cognition: Healthy body, healthy mind?”, in W. A. Rogers and A. D. Fisk (Eds.), *Human factors interventions for the health care of older adults (pp. 91-120)*. Mahwah, NJ: Erlbaum.

Levit, K. et al., 2002. “Inflation spurs health spending in 2000,” Health Affairs, Jan/Feb 2002 (on line)

Lyons, K., Gandy, M., and Starner, T. 2000 “Guided by Voices: An Audio Augmented Reality System,” Proceedings of the International Conference on Auditory Display (ICAD 2000), Atlanta, GA.

Mann, W and Helal, A. 2002. “Smart phones for the elders: Boosting the intelligence of smart homes,” Proc. 2002 AAAAI Workshop on Automation as Caregiver: the role of intelligent technology in elder care (Edmonton, CA, July 2002).

Moore, D., Essa, I., and Hayes, M., 1999. "Exploiting Human Actions and Object Context for Recognition Tasks", In Proceedings of IEEE International Conference on Computer Vision 1999 (ICCV'99), Corfu, Greece, March 1999.

Moore, and Essa, I., 2002. "Recognizing Multitasked Activities using Stochastic Context-Free Grammar", in Proceedings of AAAI Conference, Alberta, CANADA, July 2002.

Morrow, D. J., Leirer, V. O., Andrassy, J. M., Tanke, E. D., and Stine-Morrow, E. A. L., 1996. “Medication instruction design: Young and older adults schemas for taking medication”, Human Factors, 38, 556-573.

Moss, M. and Lawton, M. P., 1982. “The time budgets of older people: A window on four lifestyles”, Journal of Gerontology, 37, 115-123.

O' Brien, J., B. Bodenheimer, G. J. Brostow, and J. Hodgins, 2000. "Automatic Joint Parameter Estimation From Magnetic Motion Capture Data," Graphics Interface 2000, Montreal, CA.

Ostrom, J.R., Hammerlund, E.R., Christensen, D.B., Plein, J.B., & Kethley, A.J., 1985. “Medication usage in an elderly population”, Medical Care, 23, 157-164.

Park, D.C., & Jones, T.R., 1997. “Medication adherence and aging,” in A.D. Fisk & W.A. Rogers (Eds.), Handbook of human factors and the older adult. San Diego: Academic Press.

Picard, R.W., 1997. “Affective Computing,” MIT Press, Cambridge.

Pinhanez, C., 2001. “The Everywhere Displays Projector: A device to create ubiquitous graphical interfaces”, Proceedings of the Conference on Ubiquitous Computing,

Ramachandran,U., R. S. Nikhil, N. Harel, J. M. Rehg, K. Knobe, 1999. “Space-Time Memory: A parallel programming abstraction for interactive multimedia applications,” in Proc. ACM Principles and Practices of Parallel Programming, May 1999, Atlanta, Ga.

Reveret and Essa, I., 2001. "Visual Coding and Tracking of Speech Related Facial Motion", in Proceedings of Workshop on Cues in Communication, held in conjunction with IEEE CVPR 2001, Kauai, Hawaii, December 2001.

Rogers, W.A., Meyer, B, Walker, N., and Fisk, A. 1998. “Functional limitations to daily living tasks in the aged: A focus group analysis,” Human Factors, Volume 40, pp. 111-125.

Rogers, W. A., Mykityshyn, A. L., Campbell, R. H., and Fisk, A. D., 2001. “Only 3 easy steps? User-centered analysis of a “simple” medical device,” Ergonomics in Design, 9, 6-14.

Selinger, A. and Nelson, R.C., 2001. "Appearance-Based Object Recognition Using Multiple Views" in Proc. IEEE Conference on Computer Vision and Pattern Recognition (CVPR01), Kauai, Hawaii, December, 2001, Volume 1, 905-911.

Smith, S. et al., 1998. “The next ten years of health spending,” Health Affairs 17, 1281-40.

Starner, T. Mann, S., Rhodes, B., Levine, J. Healey, J., Kirsch, D., Picard, R.W. and Pentland, A.A., 1997 “Augmented Reality Through Wearable Computing,” Presence: Teleoperators and Virtual Environments, Volume 6, No. 4, pp. 386-398.

Thorpe, K.E., 1997. “The health system in transition, care, cost, and coverage,” Journ. Of Health politics, Policy, and Law 22, 339-361.

Tanawongsuwan and Bobick, 2001. "Gait recognition from time-normalized joint-angle trajectories in the walking plane," in Proceedings of IEEE Computer Vision and Pattern Recognition Conference (CVPR 2001), Kauai, Hawaii, December 2001.