A Synergistic Co-operative Framework of Health Diagnostic Systems for People with Disabilities and the Elderly: A Case Study

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Summary:
Millions of people worldwide have (or will due to aging) experienced some kind of unexpected disability throughout their lives. For this population, health care costs increase, quality of life and productivity decline, and in many cases family members serve as primary care assistants. Early detection and diagnosis of critical health changes could enable prevention of most of these problems, saving billions of dollars annually (Newsweek, 2006 – “Fixing the American Hospital” [31,32]). Early detection, however, requires continual vigilance. Due to the nature of their conditions or the lack of training and experience, many among this population are patients of either disinclined or unable to detect and report the critical observations that could make a difference. A common solution is for health care professionals to monitor patients directly or via relatively crude patient data collection devices; however, that solution does not scale to large populations. New generation of inexpensive, unobtrusive wearable/implanted devices automatically detect critical changes on their health condition. These devices will not be simple data collection appliances, nor will they only report variations from accepted population norms. Rather, they will learn individual user baselines and employ advanced detection and diagnostics to discover problems autonomously and signal human professionals for further assistance. These wearable/implanted systems will be engineered to integrate seamlessly both with portable equipment carried by first-responders and with fixed-location systems installed in hospitals. In addition to providing advanced detection in field, the devices will continually capture data, organize it into customized patient and condition models, and communicate each patient’s unique information to emergency and other care providers on demand.

In the project (called DIAGNOSIS) all of the major participants (WSU,PittU,TAMU,VT,Companies) are currently developing highly innovative detection methods, sensor technologies, and biomedical devices: The project fosters synergistic integration of the currently disparate research areas and the development of new technologies at the intersections of existing areas: We will make non-incremental leaps in advancing the state-of-the-art.

First the project’s structure provides sufficient longevity to maximize the impact for those with disabilities, the growing population of elderly, and the next generation of scientists, and engineers. Second, the global synergies required to cultivate true innovation are well supported by the DIAGNOSIS-Pilot model. The added value to society can be measured in billions of dollars saved in unnecessary medical expenses, creation of new industries and jobs, and priceless improvements to the quality of life of millions.

Via the project’s framework, we will implement a massive expansion of existing collaborations and partnerships to launch a diverse team, which is positioned to bridge methodological and communication gaps among traditionally disparate disciplines and produce a new generation of diagnostic and detection systems and devices.

2. BACKGROUND
The demographic imperative for the US and many other industrialized countries is that the number of older adults will increase dramatically in the next 50 years. Many older adults will become chronically ill and frail, and over half will have at least some cognitive impairment. A major challenge will be to keep them safely at home for as long as possible for several reasons: (1) home is where most people want to be; (2) institutionalization is simply too expensive; (3) wearable sensory devices could help them to take their medication; (4) keep them independent. Approximately 33% of persons over the age of 65 and 50% of persons over the age of 85 experience a fall each year [1-3]. The injuries associated with falls can have serious consequences. For example, following hip fracture, 50% of older people are unable to live independently, 25% will die within six months, and 33% die
within one year [1,3]. In one study [4], hospital admissions due to fall-related injuries (of any type) carried the highest risk of disability, with 79.4% leading to any disability, 45.2% to persistent disability, and 58.8% to disability with nursing home admission. The costs associated with falls amongst the elderly are staggering. Expenditures associated with hip fractures alone exceed $10 billion annually [2]. Overall, the cost to treat fall injuries in people age 65 or older in 1994 was $27.3 billion (in 1996 dollars) and, by 2020, the cost is expected to reach $43.8 billion (in 1996 dollars) [5].

Technology solutions to disability, lifelong or acquired with age, are commonly considered. Wheelchairs with sensory capabilities provide mobility for millions of people with physical impairments. However, the long-term reliance on the upper limbs for mobility and performing daily activities has led to an increase in the prevalence of repetitive strain injuries (RSI) and reports of pain. Upper limb RSI and pain are very common in manual wheelchair users, with carpal tunnel syndrome present in between 49% and 73% of individuals [13,14] and rotator cuff tendinopathy and shoulder pain present in between 31% and 73% [15,16]. Advances in sensor communication and IT have enabled health care providers to monitor and manage chronic diseases and detect potentially urgent or emergent conditions [17]. Health monitoring in the home environment can be accomplished by either or both of the following [18]: a) Ambulatory monitors that utilize wearable sensors and devices to record physiological signals; b) Sensors embedded in the home environment and furnishings to collect behavioral and physiological data unobtrusively. Acceptance and positive psychological impact of monitoring technology have been confirmed in studies that have included people with dementia as well as other chronic conditions [19].

Technology continues to develop. Wearable/in-planted and portable computer systems are becoming more capable. In the area of human-computer interface, applications include devices for user input, output, context awareness, and computer interfaces for persons with disabilities. More exotic items like electronic textiles (e-textiles) have generated a number of interesting applications as well as efforts involving the simulation and modeling of e-textiles [22-26]. Medical applications include sports medicine, treatment of motion-related injuries, physical therapy for stroke victims, and monitoring patients during everyday activity [27,28]. E-textiles could give patients feedback about their range of motion, tell them whether or not they are performing their exercises correctly, and record the data for analysis by a physician. Audio and video elements could be used to create notes while the patient moves [29].

The DIAGNOSIS-Pilot project will respond to these urgent needs and challenges of the disabled by offering a framework for the design, evaluation, and development of new generation wearable, portable, and fixed location systems and new generation multi-modal models for new knowledge in these emerging fields. We will combine the best existing systems with emerging sensor technologies and move the automated intelligence that detects and diagnoses into the in-field systems.

3. THE DIAGNOSIS-PILOT PROJECT

The DIAGNOSIS-Pilot project’s objectives are: (i) to develop wearable sensor-based systems for real-time, automated detection and diagnosis of health anomalies in the aging population and people with disabilities; (ii) to integrate our novel technologies into portable monitoring equipment used by first-responders. This includes enabling first-responder equipment to access and use data and derived patient models from the wearable systems; (iii) to integrate our novel technologies into fixed-location diagnostic systems installed in hospitals. Likewise, this includes enabling fixed-location systems to access and use data and models taken from the wearable systems; (iv) to create new fundamental knowledge derived from novel combinations of theoretical approaches drawn from currently disjoint areas of research; (v) to reduce healthcare costs; (vi) to enable the aging population and people with disabilities to live more independently; and (vii) to inspire and train the next generation of engineers through our transformative educational strategy.

The major fundamental and technological barriers are (i) a limited variety of sensors in common use for in-situ medical detection and diagnosis; (ii) a limited base of comprehensive theoretical foundations for accomplishing in-situ medical detection and diagnosis; (iii) lack of compatibility and interchange across the boundaries of traditionally defined research areas; and (iv) major, time consuming, regulatory hurdles in transitioning medical devices to market.

3.1 Graphical Depiction of the Strategic Plan

In this chart (fig.1), bold-bordered boxes represent activities undertaken by groups within the DIAGNOSIS-Pilot project. Thin-bordered boxes represent particularly relevant barriers and/or observations about the task environment. Thin arrows depict flows of information and/or influence. Bold arrows depict the flow of concrete product and/or system designs.

We will generate new fundamental knowledge by exploring the interactions among the four areas of theory represented in Plane 3. We will discuss that process in detail in our discussion of Thrust 1 in a later section. That fundamental knowledge will pass to the enabling technology teams, who will study means of effectively implementing usable systems with respect to practical constraints. Preliminary implementations will pass to the engineered systems test bed, where our team will integrate them with existing medical equipment to produce complete prototypes. The complete prototypes will be tested with live subject populations under the supervision of our medical and industrial team members in actual medical and production facilities. Efficacy and manufacturability information will flow back down to the Plane 2 & Plane 3 research team members to better optimize their own efforts. Mature prototypes will graduate from the testbed to our industrial team members for tech transfer and commercialization. The educational component of the center will draw material from and contribute to all three planes.

The major goal of Thrust 1 is to create the fundamental methods required to develop functioning and practical wearable, portable, and fixed-location medical detection and diagnosis systems. Our method relies on networking researchers who are experienced in component areas we have identified as vital and explore how these areas interact and
best combine with respect to wearable, portable, and fixed-location systems. The four component areas are:

### System Models
The process creates a baseline and extracts mathematical models of a system from observations of its behavior. Anomaly detection requires that the systems (wearable, portable, or fixed-location) are capable of developing a model of what is “normal” for a subject based on individualized signatures of condition baselines.

### Medical Model Informatics and Knowledge Mining
The maintenance of knowledge bases of medical information, including data and extracted models. Especially important is the ability to mine relevant information and relevant models based on partial descriptions of what is desired or needed.

### Anomaly Detection (High Speed Pattern Recognition)
Processes by which one can quickly detect an anomaly in expected behavior. High speed and low resource requirements are most critical for these purposes. Time series analysis, dynamic systems models, kernel-based pattern recognition, and statistical inference are among possible solutions for anomaly detection.

### Diagnosis Generation (High Reliability Pattern Recognition)
Processes by which one can, with great accuracy, detect the causes underlying an anomaly. Of most importance here are the minimization of false negatives and maximization of true positives. Note here that sequences of abnormal patterns map to “symptoms” and the occurrence of certain symptoms leads to a diagnosis. Our diagnosis systems will capitalize on live recordings of anomalies made by the wearable systems.

#### 3.2 Theoretical Foundation
Thrust 1 subsumes all of the activities in Plane 3 of the three-plane chart. It addresses the DIAGNOSIS-Pilot project objective (to create new fundamental knowledge derived from novel combinations of theoretical approaches drawn from currently disjoint areas of research) and associated deliverable (algorithms, patents, and research publications documenting new theoretical approaches and fundamental knowledge). Thrust 1 is also designed to help circumvent barrier (a limited base of comprehensive theoretical foundations for accomplishing in-situ medical detection and diagnosis) and the barrier (lack of compatibility and interchange across the boundaries of traditionally defined research areas).

The major goal of Thrust 2 is to create one or more wearable/in-planted systems that can autonomously learn models of specific patient/users, detect dangerous anomalies, and notify both the wearer and professional medical caregivers of impending difficulty. The specific forms of these systems will be governed by the results of pending Trust 1 activity, so complete prediction is difficult. The personnel associated with Thrust 2 all have specific expertise in creating technologies useful for wearable systems. The research team in Thrust 2 will begin by starting seed projects that will evolve into a coherent whole, once informed by Trust 1 personnel about the capabilities and limits of useful wearable technologies used by the seed projects, and developing means by which each seed technology can interact in a modular fashion with the rest. (e.g. defining common communication interfaces and/or programming APIs, formalizing power requirement specifications to enable a shared power bus architecture, etc.).

The initial goal is to create a modularized collection of sensor and wearable computer systems that can serve as an implementation substrate for a family of wearable devices that can be assembled in “plug and play fashion.” The long-term goal of Thrust 2 is to transform knowledge gained in Thrust 1 to implement working systems on that substrate.

Thrust 2 exists in Plane 2 of the three-plane chart (Fig. 1) and is labeled “Enabling Research: Wearable Systems.” It addresses the DIAGNOSIS-Pilot project objective (to develop wearable sensor-based systems for real-time, automated detection and diagnosis of health anomalies in the aging population and people with disabilities) and the associated deliverable (a set of commercially successful sensor-based wearable diagnostic and detection systems). Thrust 2 is designed to help circumvent barrier (a limited variety of sensors in common use for in-situ medical detection and diagnosis) and the barrier (a limited base of comprehensive theoretical foundations for accomplishing in-situ medical detection and diagnosis).

#### 3.3 Wearable Projects [6-12, 23,27,28, 33,36]: Here we mention by title some projects for the wearable category.

**W1: Identifying variables and behavioral signatures for falling in the Elderly.**

**W2: Electronic textiles for wearable and pervasive computing**

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**Fig. 1: It shows biometrics (facial expressions, voice and fingerprints) available in house [33,34]**
W3: Monitoring and extracting signatures of pathological behavior

The major goal of Thrust 3 is to create one or more portable systems that are a synthesis of existing first-responder equipment and our technologies. The portable systems will import data and models from the wearable system(s) as needed. The development plans for Thrust 3 mirror those of Thrust 2 except for a difference in scope and implementation hardware. A similar seed project / feedback loop with the Thrust 1 plan will be followed. Thrust 3 exists in Plane 2 of the three-plane chart and is labeled “Enabling Research: Portable Systems.” Thrust 3 addresses DIAGNOSIS-Pilot project objective ii (to integrate novel technologies into portable monitoring equipment used by first-responders) and DIAGNOSIS-Pilot project deliverable ii (a set of commercially successful portable diagnostic systems integrated with our wearable systems). Thrust 3 is designed to help circumvent barrier i (a limited variety of sensors in common use for in-situ medical detection and diagnosis) and barrier ii (a limited base of comprehensive theoretical foundations for accomplishing in-situ medical detection and diagnosis).

3.4 Portable Projects [17-19, 29, 30, 40,41]: Here we mention by title some projects for the portable category.

P1: Infrared absorption spectroscopy based on linear variable filters;
P2: Operator functional state for assessing mental workload;
P3: A portable ultrasound methodology for evaluating heart conditions;

The major goal of Thrust 4 is to create one or more fixed-location systems that are a synthesis of existing first-responder equipment and our technologies. The fixed-location systems will import data and models from the wearable system(s) as needed. The development plans for Thrust 4 mirror those of Thrust 2 except for a difference in scope and implementation hardware. A similar seed project / feedback loop with the Thrust 1 plan will be followed. Thrust 4 exists in Plane 2 of the three-plane chart and is labeled “Enabling Research: Fixed-Location Systems.” Thrust 4 addresses DIAGNOSIS-Pilot project objective iii (to integrate our novel technologies into fixed-location diagnostic systems installed in hospitals) and DIAGNOSIS-Pilot project deliverable iii (a set of commercially successful fixed-location diagnostic systems integrated with our wearable systems). Thrust 4 is designed to help circumvent barrier i (a limited variety of sensors in common use for in-situ medical detection and diagnosis) and barrier ii (a limited base of comprehensive theoretical foundations for accomplishing in-situ medical detection and diagnosis).

3.5 Fixed Location Projects [37, 38, 39]: Here we mention by title some projects for the fixed location category.

FL1: Focal 3-D microCT scanner for bone density;
FL2: Quantitative analysis of bone in 3-D;
FL3: One pass multi-sensor based evaluation of health conditions;

The major goal of Thrust 5 is to evaluate prototype systems with subject populations. Evaluation will take place in our testbed locations at local hospitals, (for fixed-location systems) and in a donated ambulance (for portable systems). Test protocols will be developed as needed. Medical and industrial team members will address regulatory considerations. Thrust 5 embeds all activities in Plane 1 of the three-plane chart. Since Plane 1/Thrust 5 results flow to Planes 2 and 3, Plane 1/Thrust 5 implicitly helps satisfy all DIAGNOSIS-Pilot project objectives and deliverables. Thrust 5 most directly addresses barriers iii (lack of compatibility and interchange across the boundaries of traditionally defined research areas) and iv (major, time consuming, regulatory hurdles in transitioning medical devices to market).

3.6 Testbeds

The testbeds will be housed in university laboratories, hospitals, a standard ambulance, and international universities and institutions. In particular, the university labs will be the first test beds for designing and testing sensor interfaces and underlying detection technologies. In addition to university lab space, the following facilities have been secured: The hospital will provide a full emergency room as available and an ER research assistant. These resources can be used to test fixed-location and portable equipment in a realistic setting. An ambulance and an Emergency Medical Technician will be used on an availability basis. These resources will be used to test portable systems in a realistic setting.

3.7 Other Important Issues

Wireless Communication with Information Security/Authentication-Authorization

For the reliable operation of our DIAGNOSIS-Pilot project a vast majority of information will be transferred exchanges via mobile digital communication. Through time, this type of communication has generated unpleasant experiences and valuable lessons of security and privacy protection from undesirable attacks and abuses. In response to these lessons, researchers and practitioners have developed software tools mainly for protecting customer’s privacy and networks security as well. Thus, security and privacy, can be achieved with information security methodologies (compression and encryption) and authentication-authorization capabilities embedded into secure processors (SP) of the communication network.

SP with Biometrics for Intelligent Authentication: Fig. 2 shows our proposed SP with biometrics capabilities offering flexibility for fast recognition of the three most common used features (fingerprints, faces, voice) and determining the level of authorization for each user.
Taking advantages of features offered by our SP architecture with biometrics capabilities, our secure networking research shall focus on developing and integrating mechanisms and protocols for secure communication and interaction in a distributed cyber infrastructure which is inherently media and technology diverse so that trusted computing can run smoothly, securely, and user-friendly.

**Intelligent Authentication Schemes** [35]: The paradigm of anywhere and anytime communication using heterogeneous technologies is inevitably intertwined with the tradeoff of security/trust and convenience. We exploit SP in authentication for secure network computing by developing algorithms that can certify intended computation being executed by untampered applications running on intended computers with secure processors.

**Context-Aware Security Mechanisms**: Future secure network interactions will take place in a pervasive computing environment, where computing and communications capabilities are increasingly embedded into everyday objects. The security goals of confidentiality, integrity, availability, authentication and non-repudiation are at once more difficult to achieve using contemporary mechanisms given the characteristics of the new environment. To provide security and trust in this environment, the security and trust mechanisms need to be context-aware. For example, a security mechanism can make use of the fact that since not all context elements are relevant all the time for building a security service, it can automatically identify and select only useful context.

4. CONCLUSION
This paper presented the general structure and operation of a model for developing a three planes (layers) synergistic and co-operative framework for early detection-diagnosis of health conditions for elderly and people with disabilities. This early diagnosis will prevent death and lower cost for millions of people by early the detection of problems that might worse health conditions, which may increase medical treatment.

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