Towards an ElderCare Living Lab for Sensor-Based Health Assessment and Physical Therapy

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Abstract—There is an increasing demand to develop innovations in eldercare technologies that can be delivered as ‘Apps’ at a cloud-scale to facilitate proactive monitoring and targeted care coordination. This article presents the design for an ‘ElderCare-as-a-SmartService’ (ECaaS) system that integrates Apps for in-home health monitoring, and remote physical therapy coaching, respectively. The focus is on the transformation of the Apps into a cloud-based living lab, which then enables on-going App development/refinement to realize a real-world enhanced living environment for eldercare that is secure, privacy-preserving and socially embedded. We detail the system and network requirements for cloud-based delivery of ECaaS Apps featuring sensor data analysis and interactive interfaces across urban, suburban and rural areas. We conclude with a proposal for sociotechnical investigations that can be lead to a human-centered design that engages older adults and care coordinators as co-developers of ECaaS, while also simultaneously improving their quality of life.

Index Terms—ElderCare Smart Service, Remote Healthcare Apps, Living Lab Design

I. INTRODUCTION

As they age, many older adults have significant challenges in managing chronic health conditions and maintaining physical functions. Early detection of health problems can help elders maintain good health and function by allowing timely health interventions. Traditional approaches of healthcare take place in medical centers or clinics, which require availability of transportation from the home. This is, however, a disadvantage for rural and sometimes suburban areas where travel distances can be very long. With emerging digital technology and multi-sensor techniques, new approaches for on-going health assessment are emerging to realize enhanced living environments (ELEs) for eldercare. While older adults stay in the home of their choice, in-home sensors can be used to monitor older adults’ activity patterns; smart algorithms recognize changes in the patterns and send health alerts to care coordinators to flag potential health changes and administer targeted coaching.

Our previous studies [1] have shown that in-home sensor data from bed, motion, and gait sensors, gathered using web services in an “App” form, can automatically provide on-going health assessments without being obtrusive. Although they can even alert care givers when the system detects health changes, alert notifications capability as provided in our App-1 are not enough. In our App-2 work [2], we have also shown how care coordinators can provide active corrective health coaching by real-time analysis of large amount of data from patient’s homes using a cloud platform. An example use case of App-2 is illustrated in Figure 1, where an interface is shown that we developed for a Physical Therapist (PT) at a clinic. The App helps the PT interact with an older adult in a home to assess his/her mental and physical health status through guided physical exercises designed to overcome fall risk.

In order to deliver such cloud-based Apps within ELEs for eldercare, the challenges that arise include: (a) ensuring stable network performance and performance-tuned cloud platforms for large-scale sensor information analysis; (b) interactive interface and intuitive displays suitable for effective interactions between older adults and PTs, and (c) the integration of Apps in their social context of use as secure, privacy-preserving and socially-embedded technologies.

Our pilot studies and conceptual work address these challenges in order to satisfy the needs of independent living, where older adults have the choice to remain in their private homes supported through a combination of on-going health monitoring and alerts along with access to on-demand remote physical therapy. In this paper, we describe the design of ElderCare-as-a-SmartService (ECaaS) along with related technical and sociotechnical challenges [3] when moving from sandbox settings in our prior works into a living lab environment, and its ultimate transformation into a real-world ELE for eldercare. Towards realizing this vision, we seek to answer bold research questions such as:

• What new kinds of web services and cloud platform issues, particularly in networking need to be investigated to deliver an effective, efficient, secure and privacy-preserving smart service system such as the ECaaS?
• How can technology play a role in the future to improve remote accessibility of ECaaS Apps? How to assess whether new ECaaS App delivery would be the same or different from either of the urban, suburban and rural user perspectives?
• What are affordances of the smart service system in an ECaaS implementation? How should the implementation be planned with regard to usability, sociotechnical, and human-centered integration?

• What new kinds of clinical studies can be enabled by the ECaaS Apps to see: (a) how much longer older adults live, (b) does it enable the family to be more aware of health status of older adults while allowing autonomy during aging in place, and (c) to what extent does ECaaS save money and improve care as well as quality of life?

The goal of our design of ECaaS and associated Apps is to ultimately develop and install on-going health assessment making it accessible for a broader group of older adults and physical therapy clinics. Towards this goal, we integrate Living Lab approaches and User Experience principles. This helps us to prepare data-driven reflections for revisiting old and new design decisions and fosters future development of cloud-based services that can be delivered in ELEs for eldercare.

II. RELATED WORK

Monitoring patients in the home for ongoing health assessment has typically been done using telehealth methods [4]. Particularly for monitoring known chronic health conditions, prior works use network-connected devices placed in the home, such as a weighing scale and a blood pressure cuff. The patient is expected to use these devices on a regular schedule such as once or twice a day. The data from the networked devices can be automatically transferred to a remote server for storage in the patient’s health record. Several studies have shown that adherence with telehealth programs decreases over time [4]. Moreover, such approaches collect only a small number of data points per day, and do not have the capability of monitoring and detecting changes in walking gait, sleep patterns, or daily activity patterns.

Our App-1 [1] overcomes the above limitation by monitoring walking gait that is particularly useful for tracking health changes. This is because, gait decline can be correlated with a variety of changes in physical, mental, or cognitive health [5]. Existing methods for measuring gait are typically infrequent and provide coarse measurements, e.g., observation by a clinician who might use a stop watch for assessment during clinic visits that occur once every 6 or 12 months. Those methods often lead to few or no objective assessments, which limit results, and therefore do not catch a person’s functional decline in a timely manner [5]. Our App-1 also builds upon new methods that use sensor technology to measure gait parameters on a continuous basis during normal daily activities. Using in-home sensor technology mounted in the patient environment, tangible information can be obtained for a variety of purposes including automated fall risk assessments, early detection of illness or change in health status, and better assessment of progress during rehabilitation or change in medication.

Vision sensors have also been proposed for home use in works such as [6]. Video cameras offer the potential to track more detailed gait information as well as other activities. However, they require calibration and more computational resources and are sensitive to lighting variations. In addition, many consumers consider video cameras in the home to be a privacy invasion, although privacy protection methods can be applied to address this problem, such as the use of silhouettes [7]. Our App-1 uses the approach of depth sensing using a depth camera in a Microsoft Kinect that captures a distance measure for each pixel. The potential of the sensor is that it offers a single, low cost sensor device and captures a three dimensional (3D) representation of the environment as shown in Figure 2. Because it captures a depth image with only shape data instead of more recognizable video images, it is deemed to be privacy-preserving. The Kinect depth sensor images are also used in our App-2 in cases where much less computational resources are necessary compared to processing long-periods of video camera streams.

Our adoption context for Kinect depth sensors in monitoring of gait in App-1 and other physical activities in App-2 is novel. There is prior work in [8], where the authors propose a method for extracting joint locations from a side view, which the Microsoft SDK (software-development kit) does not support. However, this has not been adapted for use in a naturalistic, unstructured home setting. In addition, there is prior work on tracking gait in the home using the Microsoft SDK [9]. However, this is restricted to a limited viewing area, corresponding to the constrained gaming region. Our work addresses many of these limitations [10]. We track gait parameters of walking speed, stride length, and stride time over observation time windows in multiple residential homes. Gait change and fall risk is automatically detected, which result in health alerts being sent to clinical staff. We have also validated the gait measurements in the lab using gold standard marker-based motion capture to ensure that the gait parameters extracted in the home are accurate.

The added novelty of our work is in our design to leverage the existing Apps 1 and 2 over broadband networks and a cloud platform via new interactive interfaces for both clinicians and older adults as shown previously in an example use case in Figure 1. The work closest to ours is the work in [11], where a cloud-based solution is proposed for a context management system in ambient assisted living cases. The solution features a decision support middleware to process and visualize large amounts of medical and other ambience monitoring data in real-time from a multitude of sensors and embedded devices. Two other works [12] and [13] adopted similar cloud-based approaches for eldercare, but focused on systems that support smart mobile companion robots that can be accessed via teleoperation. The authors in [12] implemented a system that uses WebRTC, Google App Engine and a fuzzy logic based software for reactive navigation capabilities during teleoperation with safety considerations such as e.g., avoiding obstacles. Similarly, authors in [13] developed a system that uses cloud computing for data computation tasks in support of robotic localization and monitoring services to empower a care giver to simultaneously manage multiple elderly patients.
We envision the ECaaS design to mimic a smart service system that integrates the two primary Apps we have previously developed using isolated sandbox approaches. In this section, we first provide our App details. Next, we outline requirements for their transformation into a secure, privacy-preserving and embedded form within a real-world ELE for eldercare.

A. ECaaS Apps

App-1 is an in-home health alert system with remote care coordination capabilities that is based on on-going analysis of sensor data obtained unobtrusively from older adult homes [1]. This App (voted ‘Best App in Health’ at the 2013 US Ignite Summit, Chicago) was developed for generation of health alerts based on hydraulic bed sensors, motion sensors, Kinect depth sensing for in-home gait analysis, and data analysis algorithms from the University of Missouri. The project involved installation of sensor networks (each generates 23 GB/person/week, even with compressed images) in 15 senior apartments in Iowa, having motion, bed and gait sensing for one year. Health alerts that are based on e.g., changes in sleep patterns were sent to clinical staff in Missouri and Iowa. A major outcome was the development of bed sensor hardware and algorithms that capture pulse, respiration, and restlessness of elders, while positioned under a mattress.

App-2 is an in-home remote physical therapy application that is hosted within a GENI testbed (i.e., Global Environment for Network Innovation cloud infrastructure supported by the National Science Foundation in the United States) and utilizes high-speed last-mile network connections [2]. This App involved an interactive interface (see example screenshot shown previously in Figure 1) that connects a PT located at a clinic to an older adult at home as illustrated in Figure 3. App-2 has been developed using Kinect sensing technologies and has been tested with five participants in Kansas City connected through Google Fiber last-mile network connections. Major outcomes include the effectiveness of the PT interface through quantitative and qualitative assessments on gait and balance using depth images and results of network performance tests.

Figure 4 shows an example set of measurements we collected during the laboratory testing and baseline performance characterization of our App-2. Specifically, the figure shows the empirical CDF (cumulative distribution function) plots of the bandwidth consumption of various stream types (audio, skeletal, color, depth) individually and in an aggregate as obtained from the Kinect API calls. We can see that a single PTaaS App session requires a peak of ≈ 200 Mbps end-to-end available bandwidth between therapist and patient sides to exchange the various data streams.

Moreover, given that the performance of the PTaaS App can be affected due to network health factors (e.g., delay, jitter, packet loss), we have tested the controlled network path between the patient and therapist sides. Thereby, we have confirmed expected and degraded behavior under good and bad network scenarios, respectively. We also identified the need for integration of cloud-based services on GENI infrastructure for the large data handling/analysis from the homes. Further, we have identified the need to deal with a lack of public IP address support in private homes with Google Fiber. These have consequently led to our on-going investigations on Layer 2 tunneling and related time synchronization for correlation analysis of Kinect sensor data, therapist/senior user experience, RGB video, depth as well as skeletal data [2].

B. Smart Service System Challenges

Several open challenges need to be solved to go beyond our isolated sandbox approaches for the Apps in order to scale them in a cloud-based smart service system of ECaaS that can be widely deployed to urban, suburban and rural areas. Our ECaaS vision is to make it suitable for embedded health assessment for: on-going assessment of health changes based on an individual’s behavior, activity patterns and baseline health conditions. We also seek to foster remote access at older adult homes involving frequent health assessments, physical therapy sessions, and health interventions, especially for those with transportation challenges, e.g., frail older adults who do not drive, or those living in rural communities with long distances to a PT clinic. In the following, we list the two salient design challenges that we believe should be critically overcome to transform the ECaaS Apps to a living lab environment for on-going development that will ultimately result in a real-world ELE for eldercare.

1) Technical Architecture Design: The first challenge refers to provisioning of a technical networking capacity that can support the ECaaS, both with and without network paths involving last-mile Gigabit fiber connections such as e.g., Google Fiber. Given that the general assumption that all end user sites will have very high-speed last-mile links is not practical, we need to ensure that the Apps delivery works properly in cases where the end-to-end network performance is unstable or not adequately tuned for satisfactory user
experience. For instance, the App configurations should handle bottleneck cases such as e.g., where a PT might want to know if the data from an older adult home is based on the actual gait measurements of balance or if the lags in the patient responsiveness data is inaccurate because of network latency or end-to-end available bandwidth problems.

2) Usability design of Apps: The second challenge pertains to the delivery of the Apps for older adults and PTs through user-friendly and interactive/immersive interface displays. The displays would need to be designed differently for the older adults and PTs in terms of the feature sets and access controls to sensor data and eldercare technology functions. Usability and user experience studies are required to provide the user interface layout and system components design for delivery best QoE to the care coordinators. This will involve iterative development with end users as co-designers right from the beginning till regular use of the Apps in practice i.e., they will need to help with the integration of the ‘Technical’ and the ‘Social’ dimensions to make the Apps be ultimately delivered as socially-embedded technologies within ELEs for eldercare.

IV. Cloud-based ECaaS Architecture

In this section, we present our vision of the cloud-based ECaaS architecture in terms of the network and computation infrastructure components and cloud services. We also describe our solutions that we obtained through experimentation, and prescribe web service development guidelines that can help realize the cloud-based ECaaS architecture in practice.

A. Network Infrastructure Solution

The cloud-based ECaaS architecture relies on high-speed broadband connections between the older adult’s home, the App provider (i.e., the clinic) site, as well as the ECaaS Apps hosted within a cloud infrastructure. In order to develop a reference implementation of our proposed ECaaS architecture, we have setup a novel peer-to-peer App deployment infrastructure that integrates related technology components as illustrated in Figure 5. Our solution approach facilitates App services intercommunication, as well as is suitable for security purposes if sensitive information is being exchanged between the App provider and older adult sites. Further, to meet the large data movement tasks in cloud service interactions, and to satisfy the real-time requirements in the sensor data analysis, we have experimented with a variety of network configurations for network overlay setup between the various sites based on virtual link (Layer 2) technologies. For the out-of-band communications to support data processing with App-related data logs, we utilize regular Internet (Layer 3) protocols.

Through extensive performance troubleshooting of software and hardware virtualization alternatives provided by the Brocade Vyatta vRouter, we have engineered the overlay paths to satisfy the fast data movement requirements of video, audio, RGB, depth and skeletal data for real-time display of gait and other movement parameters at both ends. Given that private home access network connections in Google Fiberhoods as well as in other home network settings do not have public IP addresses, our overlay network solution was also helpful in cases where our PT interactive interface (example screenshot shown previously in Figure 1) needed binding of ports between the App provider and older adult home ends to allow custom protocol communications.

B. Computation Infrastructure Solution

MU’s hydraulic bed sensors as well sensors for motion and gait data collection are installed as part of the App-1 deployment. In the case of the App-2 deployment, the interactive interfaces on both the PT and older adult ends use a Kinect device along with a local computer (specifications: Windows 7 64 bits, RAM 4 GB, Storage 500 GB, Gigabit NIC) that is mounted on a mobile cart that has a large display (specification: 1920x1080 px). The application, system and network performance data across the ECaaS supporting infrastructure are processed locally for tasks such as preliminary sanitization and meta data annotation (e.g., data folder naming), and are immediately sent to a cloud-hosted database for detailed data processing that help with later activity report discussions between the care coordinators and the older adults.
We utilize a GENI Rack i.e., a community cloud infrastructure for the database hosting to handle data management tasks. We also use the GENI Rack to host the peer-to-peer application orchestration signaling co-ordination module that is part of the overlay networking setup described previously. For these purposes, the GENI Rack is configured with three virtual machines provisioned using the VMware ESXi hypervisor. The entire application, system and network performance data collection, aggregation and visualization are performed with our Narada Metrics software [15], which was developed previously as an end-to-end network and application performance measurement framework [2].

C. Cloud Services Solution

For high-scale delivery of the ECaaS Apps within a cloud-based infrastructure, we prescribe two layers of services with REST (REpresentational State Transfer) web services abstractions that are commonly used in cloud platforms viz., (i) Secure Compute and Network Services, and (ii) Data Services. In Figure 6, we show our App-2 i.e., PhysicalTherapy-as-a-Service (PTaaS) within the cloud-based ECaaS architecture. A challenge in the infrastructure configuration for secure services refers to compliance issues (i.e., pertaining to FISMA (Federal Information Security Management Act) Moderate or HIPAA (Health Insurance Portability and Accountability Act)) that are paramount in the health care related technology infrastructures.

![Fig. 6. ECaaS cloud-based services architecture for PTaaS App delivery.](image)

In the first layer, different processing pipelines should be developed that handle the workflow, security issues for the large amount of data-in-motion (e.g., SSL (Secure Sockets Layer)), and the access control as well as encryption for the high volume data-at-rest. The access control for security management need to be implemented using Federated Identity and Access Management frameworks such as Shibboleth. We suggest that custom web interfaces be developed for the owners of the PTaaS system to be able to add, delete or modify permissions of the different data query, analysis and visualization tasks. In the second layer, components are related to data services that operate in virtualized storage environments and need to be federated across multiple private cloud (e.g., hospital data center) and public cloud (e.g., Amazon Web Services) platforms.

While making these decisions in the beginning and assessing their impact, our approach is to use the co-design and continuous monitoring approach with frameworks such as Narada Metrics. This approach allows us to query data from multiple sources, and feed the results to tools that perform data analysis and visualization to indicate salient trends or bottleneck anomaly events. This procedure helps to reflect on decisions while using ECaaS with the goal to confirm, renew or to revise them based on given data by App-1 and App-2 performance evaluations in a controlled environment.

D. Network Quality Estimator

We tested the health alert system of App-1 in senior housing with face-to-face clinical care coordination. However, as implemented currently, the approach does not scale well. Sensor data that was collected in the home is over 23 GB per week per elder. To transfer that data in a timely manner to support health alerts has been hard to achieve consistently. Moreover, the relational database methods that have been applied, have not allowed fast interactive access for huge databases. These technical issues involving local data processing at the network-edge i.e., at the elder homes can be addressed through the emerging paradigm of ‘fog computing’ to meet latency bottlenecks for interactive data analysis. For instance, the GENI Rack compute services can be intelligently coordinated with a local compute service that can intelligently perform pre-processing at the patient side, and post-processing at the clinical care coordinator side based on the estimation of network quality constraints at the end sites. However, such a fog computing architecture in ECaaS will introduce security/privacy issues that need to be considered carefully in the data storage and data access configurations [14].

In the case of App-2, ECaaS relies heavily on video conferencing for remote care coordination, and thus requires high performance (≈ 200 Mbps) for accurately recognizing facial expressions, skin color, eye clarity, and speech patterns, as well as inspection of depth data in real-time at the PT side. A robust network architecture with predictable end-to-end performance is essential for the interactive monitoring and health interventions. We approach this design challenge by instrumenting the App-2 to obtain measurements for network quality estimation. Both active measurements (i.e., end-to-end TCP throughput, round-trip time (RTT) delay, jitter and packet loss) and passive measurements (i.e., transfer rate on uplink of the local interface, download rate at remote interface) are being collected using the Narada Metrics measurement framework [15].

The technical challenges for integrating the ECaaS App-1 and App-2 point to several design options. We argue that a good start for ECaaS is the integration with remote deployment of sensing, Big Data analysis methods for storing and accessing consumer data, high-definition video-based communication, HIPAA-compliant security, and interactive interfaces, leveraging cloud computing and overlay network channels. For this integration, we are starting efforts to use and test the newly deployed fiber networking infrastructures within urban, suburban and rural communities in the state of Missouri. We have established on-going partnerships with healthcare providers and Gigabit fiber connection providers (e.g., Google Fiber, Co-Mo Connect, MOREnet) in these efforts in order to translate our research into real-world ELEs for eldercare.
V. A Living Lab Environment for ECaaS

We conceptualize the living lab for ECaaS as combination of technology, network optimization and cloud-based integration of our two Apps that is also extensible for other future Apps. We are working towards building a living lab environment that involves eight private homes of senior adults in urban, suburban and rural areas, as well as several local PT clinics in the Missouri region. We have access to a few of these homes and PT clinics from previous projects and through our project partners of Google Fiber and Co-Mo Connect. Our next step of development of ECaaS as “design-in-use” within a living lab environment is guided by data-driven design-based research approaches such as usability testing, data analytics and iterative design testing with end-users.

We address three research approaches that we plan to pursue to deliver ECaaS to users in a manner that is performance optimized for satisfactory user experience. The three research approaches and the corresponding research questions are described in the following:

A. Cloud Service Management Studies

Huge amounts of data in real time can cause irritations for the users due to technical network problems (e.g., delays in providing data). The care coordinator or PT needs to be able to confidently assess whether non-ideal performance in the exercise forms of an older adult is being impacted due to lag in network communications in data-intensive interactive sessions, or in fact is impacted due to the physical and cognitive limitations of the older adult. The research questions to be answered include: How to optimize networks and cloud systems for ECaaS using health assessment data in remote settings? How to perform troubleshooting in bottleneck cases? [2]

B. Data Analytics Studies

Gait information needs to be presented back to older adults in-home and in a clear, understandable formats. Further, the Apps need to provide pertinent information that fosters feedback to patients, PTs or care providers to take suitable actions in cases where proactive care is essential. An important research question here is: What sensor information for automated health alerts needs to be fused for real-time analysis and optimization when in remote use?

C. Usability and Human-centered Development Studies

There needs to be an integration of the Apps into their context of use through sociotechnical design configurations such that patients, care coordinators and PTs will actually use the Apps in a sustained manner, instead of avoiding them. Important research questions include: How to integrate the sensors and Apps into private homes, and PT clinics such that they will become part of a sociotechnical system that supports co-evolutionary growth? Which interface layouts work best for the older adults, care coordinators and PTs in the context of being user friendly, effective and efficient? [16].

The above sociotechnical studies and system development involves agile iterative design testing, usability studies with end-users as co-designers, as well as data collection by adopting the SocioTechnical WalkThrough (STWT) method [17]. The STWT is a qualitative co-design workshop method based on Focus Group interviews in which the PTs and patients become co-designers of ECaaS and ‘model’ the ECaaS in practice. STWT is moderated by an experienced research team member in a series of workshops (typically up to 6 workshops per year) to explore the users’ perspectives and measure the benefits of ECaaS. Each workshop lasts 2 to 3 hours, and the obtained results are organized as “case vignettes” [18]. The case vignettes inform the iterative and agile software development of ECaaS to produce user-friendly solutions.

VI. CONCLUSION AND OUTLOOK

In this article, we presented the design of an ‘ElderCare-as-a-SmartService’ (ECaaS) system that can facilitate proactive health monitoring and targeted care coordination of older adults within their in-home settings. We detailed the challenges in the cloud transformation of sandbox approaches of ECaaS Apps into a living lab environment with actual users. The living lab purpose is to facilitate on-going App development to ultimately create real-world ELEs for eldercare. We not only focused on the technical design of the infrastructures and Apps development, but argued how the social and organizational design needs to be considered within the context of ECaaS use in practice i.e., within the organization of clinics, PTs and their workflows as well as the environments and daily processes of patients’ in-home settings.

We outlined how a “co-development” strategy that involves the stakeholders to assume relevant roles (i.e., health care providers serving as App owners, as well as older adult end-users serving as App consumers) in order to work together to make ECaaS into a highly secure, privacy-preserving and socially embedded smart service system. Our suggested approach was to apply different methods of usability and human-centered design concepts such as the SocioTechnical WalkThrough to help stakeholders to adopt the ECaaS and refine it during ‘design-in-use’ within a living lab environment.

Further research of ECaaS activities based on our design presented in this paper can enhance understanding at the level of sociotechnical configurations for ELEs targeted for eldercare. In particular, our proposed efforts to obtain user surveys and conduct behavior modeling with end users will lead to useful interactive interfaces for the ECaaS Apps that improve clinical care coordination. In addition, they enable studies of cloud-based services to effectively handle the video and audio streams through metrics of usability, user satisfaction, and App effectiveness for eldercare that can be seamlessly delivered across urban, suburban and rural areas. Thus, our ECaaS design has the potential to improve quality of life for older adults and their care coordinators through pertinent social embedding of Apps within ELEs for eldercare.
REFERENCES


