CAL: A Smart Home Environment for Monitoring Cognitive Decline

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***Abstract*—The increased growth of the aging population (i.e., 65 years or older) has led to emerging technologies in health care that provide in-home support to patients using devices throughout the household. Such smart home environments can monitor and interact with patients and their doctors/caregivers to augment patient medical data for diagnosis than can be generated via traditional doctor visits. Moreover, smart homes are enabling older adults to stay at home longer as opposed to permanent moves to assisted living or nursing facilities, increasing health and well-being and decreasing overall costs to the individual and society at large. This paper proposes Cognitive Assisted Living (CAL), a cyber-physical system comprising a network of embedded devices for collecting and analyzing patient speech patterns over time for monitoring cognitive function beginning in the early stages of Alzheimer's disease. Specifically, CAL will analyze patient speech patterns and spatial abilities, via a set of daily interactions, to provide a longitudinal analysis of speech deterioration, a significant indicator of cognitive decline resulting from Alzheimer's disease. Understanding the rate of cognitive decline can enable caregivers and health care professionals to better manage the patient's daily care and medical requirements. Additionally, the patient's cognitive state can be shared across household devices to increase the patient's comfort and better accommodate lifestyle changes. To these ends, we describe the architecture of the proposed system, the methods to which we will detect cognitive decline, and specify how the system will provide continuing fault tolerance and data security at run time.**

***Index Terms*—smart home, multi-agent systems, cyber-physical systems, health care, software engineering**

I. Introduction

Over the course of the next 12 years, the population of people aged 65 and older will grow by roughly 60% while the growth of the youth population will stagnate [1], [2]. With the increase in persons living to older ages comes a parallel increase in the number of age-related diseases, such as various forms of cancer and dementia. Currently, there are over 5.5 million people in the United States alone that have been diagnosed with Alzheimer's disease, with a new diagnosis occurring approximately every 66 seconds [3]. In 2016 alone, 15 million family/friends provided *unpaid* care to those with Alzheimer's disease, with services rendered estimating nearly 230 billion US dollars and projections reaching 1.1 trillion US dollars by 2050 [3]. Alzheimer's disease is the only top-ten leading cause of death that has no effective treatment. Caregivers (both from the health care industry and family/friends) require methods for managing Alzheimer's in a cost effective and useful nature. To this end, we introduce Cognitive Assisted Living (CAL), a smart home environment for supporting patients with early-stage Alzheimer's disease, focusing on monitoring cognitive function over time while managing software concerns such as security and privacy in a cyber-physical, multi-agent system (MAS) environment.

Recently, there has been extensive research done in the smart home domain, including homes that focus on health care initiatives [4]–[6]. Such systems implement a network of devices throughout a home to support day-to-day living activities, including in-home care of patients. When dealing with issues of health care, data privacy and security is a major concern and must be appropriately managed [7], especially for a system that has the ability to passively monitor a patient throughout the day. Moreover, such systems must be able to handle patients with changing needs [6], as there may exist issues where patients remove monitoring devices (e.g., smart watches), disable thermostats inadvertently, or engage in dangerous activities resulting from cognitive decline. Smart homes, therefore, serve as an opportunity to support patients in-home while managing manifesting symptoms.

To this end, we propose an integrated CAL system to provide care to patients suffering from Alzheimer's disease from the comfort of their homes, thus reducing the confusion and stress imposed by a transfer to an extended care facility [8]. At least once per day, a device with user interface capabilities interacts with the patient and asks a series of questions typically done in a doctor's office. A series of natural language processing (NLP) techniques will analyze the grammar, syntax, vocabulary, and accuracy of the patient's answers to provide indicators of the patient's cognitive state. Additionally, this information is sent to medical professionals for further analysis, as patient feedback cannot always be reliable. The system will then ensure that data is secured, private, and available to both authorized users and other devices within the system.

The remainder of this paper is structured as follows. Section II provides background information on early-stage Alzheimer's disease, smart home infrastructures, multi-agent systems (MAS), and natural language processing (NLP). Section III details our motivating example and the CAL environment. Following, Section IV presents related work. Lastly, Section V provides a discussion of our work and presents future directions.

II. Background

This section provides relevant background information on early-stage Alzheimer's disease, smart homes, MASs, and NLP.

A. Early-Stage Alzheimer's Disease

There are over two dozen different types of dementia that have been identified, with the most common being Alzheimer's disease [3]. Alzheimer's is a progressive degenerative disease caused by plaques and proteins that litter the brain and is responsible for losses in neuron functioning and ultimately the shrinking and deterioration of the brain over time [3]. Alzheimer's disease is culturally synonymous with memory loss, but Alzheimer's destroys many other parts of an individual's cognitive functioning including changes in behavior (a once gentle person becomes angry and aggressive), losses in spatial and reasoning abilities (can no longer balance a checkbook, doesn't understand appropriate money use, is clearly a danger driving a car) as well as progressive aphasia (the gradual loss of speech abilities) [3].

Neurodegeneration from Alzheimer's disease occurs from a years-long process of brain atrophy. The disease, however, is evident in the brain well before there is any clear outward indication that a problem exists [3]. Many people in the early stages of Alzheimer's disease can still function independently. However, because it is a progressive illness, individuals with Alzheimer's will eventually require help with activities of daily living (ADLs) and instrumental activities of daily living (IADLS) [9]. Progression into mild and moderate Alzheimer's dementia can cause many problems, including disruption to sleep patterns (e.g., insomnia), wandering/getting lost, and trying to use potentially dangerous appliances (e.g., stoves and microwaves) without remembering their purpose or forgetting to turn them off [3], [9].

B. Smart Homes

Smart homes typically comprise a network of intelligent devices, generally in an Internet of Things (IoT) ecosystem, to provide its users with a wealth of services not normally provided by a standard home [6]. For example, a smart home may provide voice-activated capabilities (e.g., Amazon Alexa and Google Home) for information retrieval, intelligent temperature control (e.g., Nest), and monitoring the contents of a refrigerator [4], [10]. The devices that power this ecosystem are generally low-power, low-cost, and leverage the WiFi capabilities of a home network to provide such services. Moreover, a smart home is an example of a cyber-physical system (CPS), or a system that must manage concerns resulting from the interactions (either intended or unintended) of the cyber and physical domains. For example, one CPS concern is the impact that hardware processing imparts onto software timing, where real-world problems may cause a delay in processing critical instructions, thereby leading to timing violations that cause a breakdown in the system. Cloud services are also being integrated into smart homes to provide additional capabilities not normally feasible in the context of local embedded systems (e.g., machine learning, speech recognition, etc.).

In the context of a medically-oriented smart home, services can include ensuring that patients are correctly consuming prescription medicine, monitoring patient health statistics (e.g., heart rate, blood pressure, etc.), and monitoring water consumption [4], [10]. To this end, the CAL infrastructure focuses on leveraging common devices, coupled with cloud services, to provide both a quality of living and service that benefits a patient with early-stage Alzheimer's disease. Security and data privacy is a major concern in this domain, as patient data is highly-protected and cannot be shared openly. In a smart home, data transfer to and from cloud services must also be protected and anonymized to, at minimum, HIPAA standards [7].

C. Multi-Agent Systems

An MAS is typically instantiated as a distributed system that comprises multiple agents (e.g., separate devices or virtual processes) that each act independently towards a common set of shared objectives, both local (i.e., for each agent) and global (i.e., for the system as a whole) [11], [12]. Agents are generally reactive in that they monitor the system's operating context and adapt as necessary to continually fulfill their objectives in an autonomous fashion. In the context of CAL, each separate device acts as an autonomous agent and communicates via WiFi.

As an MAS is generally intended to be a long-running system, run-time requirements monitoring [13], run-time testing [14], and run-time verification [15] have been proposed to enhance assurance that the system is behaving as expected, both informally and formally. Generally, a set of software artifacts (i.e., requirements specification, test specification, linear temporal logic model, etc.) are used to fulfill the corresponding assurance technique. In terms of an MAS, such activities can be performed at run time either by leveraging unused processor cycles [16] or additional agents [17].

Natural Language Processing. NLP is a methodology for understanding both the structure and meaning behind a given language. NLP is being increasingly used in medical applications to understand doctor notes and other forms of medical reports [18]–[20], with existing technologies such as Gensim and Google Cloud Speech API[1] providing the means for easily performing NLP tasks and speech-to-text translation, respectively. We will expand further on the methods and techniques to be used for case studies in Section III.

III. SmartHome Environment

This section details our motivating example and the CAL architecture.

[1]See https://radimrehurek.com/gensim/ and https://cloud.google.com/speech.

A. Detecting Speech Deterioration

A patient in the early stages of Alzheimer's generally can interact with devices such as phones or tablets on a daily basis [3]. However, device usage becomes difficult as cognitive capabilities decline. To detect this decline, CAL will monitor the patient's speech and motor skills daily via a device application (i.e., Android application) that has the patient take a medical survey. The system stores a history of patient responses, both verbal and spatial. For example, a patient may be required to draw a clock with hour and minute hands pointing to a specified time, or respond to questions such as "What did you do today?" Typically, a doctor will perform such a survey during a visit, however that data only demonstrates a small snapshot of cognitive function. CAL will perform this task daily (with questions varied per day). CAL stores user responses and can perform an analysis (both lexical and graphical) to determine, in a very fine-grained manner, the state of the patient's cognitive functions. This state can indicate the velocity of a patient's decline, where velocity may be fairly steady-state (e.g., no relative change in cognitive capability) or demonstrates clear and steady decline (e.g., patient becomes confused, cannot speak a fully-coherent sentence, etc.).

To illustrate this procedure, consider again the question "What did you do today?" Assume that the patient is asked this question once per week for a period of a year. The patient may have varying responses to this question depending on their mood, their level of activity, etc. If this question were asked at a single point in time (e.g., at a doctor visit), the response may not necessarily be fully reflective of the patient's cognitive state. CAL will continually monitor patient responses, leveraging NLP and statistical techniques, to determine if a patient's speech patterns have begun deteriorating. For instance, if the patient transitions from full sentences with a rich vocabulary to clipped sentences with a minimized vocabulary, on multiple occasions, then CAL will notify the health care provider of the indicator. It is then up to the health care provider to determine if cognitive function has actually started to decline. Depending on the patient's state, CAL may be able to adapt to support the patient (i.e., in the case where the patient is capable of self-care) or suggest that a medically-qualified professional intervene.

Rate of Cognitive Decline. Patients suffering from Alzheimer's disease do not often present symptoms all at once. Rather, there is a steady, relatively slow decline that begins well before it can be detected or diagnosed. The disease can be fairly progressed once a decline has reached a point of concern for the individual/caregivers. To provide an indication of the patient's cognitive state, a series of standardized surveys can be given that test the patient's speech and spatial skills. Such skills aim to establish the patient's base level of prosody (patterns/rhythms of speech), fluency, etc. For instance, Question 1 provides a sample question that may be posed to a patient to monitor speech and Question 2 provides a sample question that monitors spatial response.[2]

Can you tell me something that happened in the news recently? (1)

Please draw a circle and mark in the numbers to indicate the hours of a clock. (2)

Responses to Question 1 will naturally vary on a week-by-week basis, depending on the patient's mood, level of tiredness, etc. However, responses to questions such as this can provide a great amount of detail regarding cognitive function. For instance, indicators that a patient is beginning to decline may present as a result of using fewer words consistently, relying on words with similar syllable lengths, and using less diverse words (i.e., a reduction in vocabulary size) [9].

Question 2 has the patient perform a drawing task. Again, a longitudinal analysis of patient decline can be provided by monitoring this type of prompt. Analyzing the patient's ability to draw a clock tests the individual's spatial abilities, another major indicator of cognitive functioning, thus providing evidence for health care professionals to determine and treat the patient's needs in real time. However, for this initial research we focus on verbal decline.

The end goal of this process is to provide authorized parties with enough information to make both an accurate diagnosis of patient cognitive state as well as to provide the required level of care. Again, the intent of this system is to ensure that patients remain as comfortable as possible with the required level of care/support needed, and as such, CAL will enable patients progressing through early-stage Alzheimer's to stay at home while cognitive function allows. Generally, an individual will have better outcomes if a diagnosis and treatment are performed early. Although no effective treatments exist to slow or cure the disease, there are pharmaceutical, dietary, and activity-related treatments that can help alleviate the symptoms. CAL can act as an early intervention mechanism to help detect new symptoms, recommend a doctor's visit, and result in a new treatment plan to alleviate experienced symptoms rather than waiting for periodic physician visits.

B. CAL Architecture

Detection of early-stage Alzheimer's, as well as monitoring the velocity of patient decline, is a non-trivial task, where CAL is intended to enhance traditional diagnosis procedures. CAL is a CPS modeled with multi-agent characteristics, where each agent provides a decentralized service. Figure 1 presents the general architecture of CAL. Note that, while this system is modular in nature and can support multiple goals, to effectively scope this research we focus on *speech deterioration* only.

(A) Patient Interface. A tablet (i.e., Android Nexus 9) will provide a central interface for the patient to interact with the CAL ecosystem.[3] This interface will facilitate patient

[2]Questions 1 and 2 were drawn from the *General Practitioner Assessment of Cognition* survey provided by the Alzheimer's Association (http://alz.org).

[3]While other device types/manufacturers are readily available, for ease of programming we focus on Android as it is open source.

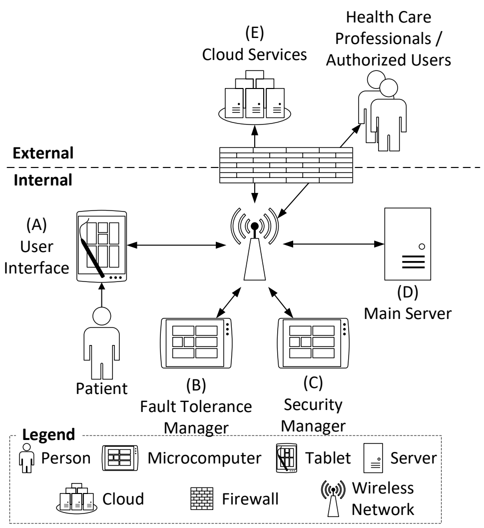

Fig. 1. CAL architecture.

interaction with a daily survey provided by health care partners, where similar surveys are provided by a multitude of professional health care entities. The patient will be prompted each morning to respond to a pre-determined set of questions drawn from these surveys, where questions will not repeated each day unless otherwise required (i.e., to prevent question stagnation). The questions can be answered either by speaking to the device or drawing on the device by touch/pen. The interface will then send the test results to the *Security Manager* agent for encryption and storage on the *Main Server*.

(B) Fault Tolerance Manager. This agent (i.e., a Raspberry Pi) will periodically scan all connected agents for weaknesses/shortcomings in terms of associated software artifacts (e.g., requirements specification, goal models, formal models, etc.). Fault tolerance will comprise run-time requirements monitoring [13], run-time testing [14], and run-time verification [15] of software artifacts to ensure that each agent is behaving as expected and is able to tolerate fluctuations in the system and environment that result from uncertainty (e.g., system misconfiguration, misunderstood requirements, human element, unexpected weather conditions, etc.) [21].

(C) Security Manager. The *Security Manager* (i.e., a Raspberry Pi) will also periodically scan the CAL network for signs of intrusion or insecure agents. For instance, this agent will have access to all system access logs for discovering non-allowed access entries and will be able to run monitoring software such as TripWire[4] to identify whether any vulnerabilities in either the agents or the network configuration exist. Lastly, the *Security Manager* will ensure that all data is encrypted/decrypted appropriately, and that any data sent publicly is either anonymized or redacted as required by HIPAA privacy standards [7].

(D) Main Server. The server provides a central repository for system data and acts as a broker between the CAL environment and *Cloud Services*. This server will enable long-term storage of data (in encrypted format) to provide the historical view of patient responses. Moreover, this agent will initiate all cloud-related activities (via lambda function calls), including speech-to-text translation, NLP techniques, and statistical analyses. This agent will also be responsible for generating daily reports and communicating with authorized users.

(E) Cloud Services. Existing cloud services (i.e., Google Cloud Speech API) will be used to convert patient speech to text and perform other heavy-processing tasks (e.g., NLP and statistical analyses). Depending on the needs of the particular NLP/statistical technique, data may be remotely stored while a model is trained, however upon completion all data must be removed or relocated to CAL-controlled devices. Note that, due to security/privacy concerns, data may need to be encrypted and/or anonymized as per HIPAA standards prior to external transmission [7].

Health Care Providers / Authorized Users. Both health care providers (e.g., primary care physician, nursing staff, etc.) and authorized users (e.g., family members) have access to confidential system information regarding patient data, with multiple levels of authorization enabling access to different types of data. For instance, medical professionals may have access to sensitive information relating to personal information, whereas family members do not necessarily need to know such detailed information. However, authorized users could access less critical information, such as if the patient is awake, asleep, in distress, requires medication, etc.

To demonstrate patient status, CAL will publish daily reports to health care providers. Such reports will contain filtered data from all available sensors (with additional information provided as requested), where available sensors comprise devices embedded within CAL as well as any wearable devices/sensors that have been required by medical staff.[5] Moreover, CAL will also provide a summary analysis of the patient's speech patterns on a daily basis, where an NLP analysis will be performed to determine the patient's rate of decline.

Upon determination that the patient has entered a critical state (e.g., significant decline in cognitive function, medical emergency, etc.), CAL will notify health care providers and emergency services immediately.

C. Detection of Cognitive Deterioration

We now present our initial work towards detecting cognitive function using the distributed architecture of CAL. Whereas the *Fault Tolerance* and *Security* agents focus on ensuring that the system itself continues to function as expected, the *Patient Interface* and *Cloud Services* will focus on detecting patient cognitive function. Note that at this point we are strictly focused on monitoring cognitive decline, not necessarily emergency states. For such states, additional sensors/devices will be necessary.

Following patient interaction, CAL agents will ensure that data is properly parsed, encrypted, and stored. CAL then initi-

[4]See http://tripwire.com.

[5]Note that wearables are not included in the architecture, however devices such as smartwatches or sensors can optionally provide medically-relevant data such as heart rate, blood pressure, etc.

ates a *cognitive testing cycle* where the most recent interaction will be compared with prior data. For the purposes of this initial research, we focus on sentence degradation in terms of structure, vocabulary, and semantic intent. To these ends, we consider the following metrics as potential indicators of cognitive decline:

1) Number of syllables per word
2) Sentence length and validity
3) Word complexity and validity

Note that other metrics, such as slurred speech and spatial consistency, will require additional detection mechanisms that are outside the scope of this work as we focus on the *spoken* indicators.

To address these metrics, our NLP techniques will use several essential components of language to automatically extract a rich set of linguistic features and lexical information from patient responses, including both syntactic sentence structure and semantic meaning. Over time a model will emerge of "normal" patient responses that provides a picture of average word complexity and sentence structure/rhythm for the patient under observation. The cognitive model will be enabled by a composition of multiple NLP techniques, including part of speech (POS) tagging, syllable based N-gram model, term frequency-inverse document frequency (TF-IDF), and latent semantic analysis (LSA) to accurately measure our metrics [22]. The combined result of these techniques produce NLP features, where features can be used to perform information extraction and text classification. We anticipate that, following tokenization of sentences, the syllable N-gram model will support syllable count discovery, and LSA, TF-IDF, and POS will address word validity/sentence validity [23]–[25]. The rate of cognitive decline then, as determined by monitoring patient speech patterns, depends on the distance between "normal" and measured metrics.

D. Illustrative Example

This section presents a scenario in which CAL interacts with a patient named Alice. Alice wakes up at 7:00am and begins her day. Her normal routine is to have breakfast and coffee at 8:00am. At 8:30am, the *Patient Interface* will notify Alice that it is time to take her daily survey. Alice then interacts with the *Patient Interface* by selecting that she is ready to begin the survey. CAL selects a number of questions from its database of survey options, ensuring both variety and an acceptable ratio of verbal to spatial questions. Alice finishes her survey and the *Interface* prepares the recorded data for parsing. All verbal responses are parsed using *Cloud Services* (i.e., Google Cloud Speech API). Verbal responses, including parsed text, are encrypted by the *Security Manager* and stored to a local database within the *Main Server*. Spatial responses, unless otherwise required, are stored in the *Main Server* unencrypted. As patient privacy is a major concern for CAL, the system will need to decrypt all necessary data each time a cognitive testing cycle is performed.

Next, CAL will perform a cognitive testing cycle. The most recent responses held in memory are compared to the system's database of prior responses. The system would then decrypt the response database to perform its analysis. Assume that 10 survey questions expecting verbal responses were asked. Each response is lexically analyzed based on the provided metrics and compared to all other responses. A report is then compiled that details how different/diverse Alice's answers are from the database of existing responses. Health care providers are sent a copy of the report, and if the system determines that Alice may be at risk, local caregivers (e.g., family) may be notified.

Threats to validity. This paper presented CAL, a system for supporting a patient that has early-stage Alzheimer's disease. Thus far we've identified the following threats to validity. First, the system relies on third-party speech-to-text tools (i.e., Google Cloud Speech API) to parse spoken words to text. Such a system is not perfect by any means and therefore words may be parsed incorrectly. As a result, some measure of error must be considered when determining cognitive function. Second, our system requires that a patient accept a certain level of intrusiveness into their daily life from passive monitoring of speech. Therefore, the patient must become comfortable with such a system and act as they normally would (i.e., the patient should not try to speak differently to "game" the system). Third, the system presented is conceptual in nature and therefore may not necessarily translate exactly to a real system.

IV. Related Work

This section presents related work on ambient-assisted living (AAL) homes and ubiquitous computing.

A. Ambient Assisted Living and Ubiquitous Computing

Enabling patients to stay at home has long been a focus of the CPS domain, where AAL systems can support patients in day-to-day activities and provide limited in-home care [4]. For instance, the VirtualECare framework from Costa *et al.* conceptualizes AAL as an MAS using existing programming standards [5]. Whereas this framework is intended to be a general in-home support system, CAL focuses on the highly-specific symptoms of Alzheimer's disease, but can be extended to support other in-home care activities. The Aware Home Research Initiative provides a ubiquitous environment throughout the home to support a wide range of types of in-home patient care, including elderly and autistic patients [6]. Conversely, CAL focuses specifically on an MAS architecture that facilitates longitudinal analysis of patient data, in this case, cognitive decline. Software engineering techniques such as RELAX have been applied to AAL-related case studies to enhance software assurance as uncertainty manifests [10]. We intend to examine how techniques such as RELAX can be applied to our system to effectively mitigate uncertainty experienced as a result of failing sensors, communications breakdown, and security concerns.

Ubiquitous computing supports the smart home environment by embedding computing in nearly any device and is a feature of the IoT paradigm. With ubiquitous computing comes the ability for a user to interact with devices capable of both accepting user input as well as input from passively monitoring its environment. This capability has wide reach into the health care domain, enabling devices and sensors to be placed within a household and leverage new types of user interfaces, such as NLP, gesture-based inputs, and automated capture via video [26]. Moreover, ubiquitous computing enables *context-awareness* recognition, or the ability of the system to determine both user actions and environment state [26], [27]. By comparison, the CAL architecture supports ubiquitous computing, albeit with a focus on minimally embedding devices only as necessary. Furthermore, CAL leverages NLP techniques for cognitive deterioration detection with future plans to incorporate cameras for further in-home support of visual cues (e.g., wandering, fall risks, etc.).

V. Discussion

This paper has presented a conceptual framework for a smart home environment, CAL, to be used for supporting early-stage Alzheimer's patients in a comfortable setting at home. CAL is a multi-agent CPS that continuously monitors the patient's cognitive state via a longitudinal analysis of patient responses to daily survey questions. The analysis of patient response is facilitated via participating cloud services that use NLP techniques to detect a deterioration or breakdown in patient speech patterns, indicating signs of cognitive decline and thereby requiring a shift in the patient's care strategy. We motivated CAL in terms of an illustrative example that serves as a basis for our proof-of-concept study.

Future work for this research includes introducing self-adaptive features into CAL to enable run-time reconfiguration capabilities in response to uncertainty or adversity, implementation of our conceptual system in a real-world environment, and long-term clinical studies to determine the effectiveness of our NLP-focused strategy.

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