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REAL WORLD, LARGE SCALE IOT SYSTEMS FOR COMMUNITY ELDERCARE: EXPERIENCES AND LESSONS LEARNED

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ABSTRACT

The paradigm of aging-in-place - where the elderly live and age in their own homes, independently and safely, with care provided by the community - is compelling, especially in societies that face both shortages in institutionalized eldercare resources, and rapidly-aging populations. When the number of elderly who live alone rises rapidly, support and care

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from their communities become increasingly critical. Internet-of-Things (IoT) technologies, particularly in-home monitoring solutions, are becoming mature. They can become the fundamental enabler for smart community eldercare. In this chapter, we share our real-world experiences gleaned from an ongoing large-scale project on IoT-enabled community eldercare. We identify technology-centric challenges that need to be addressed, so that such systems can be sustainably implemented and adopted by key stakeholders.

Keywords: smart homes, unobtrusive sensing, in-home monitoring, community eldercare, Internet of Things

1. INTRODUCTION

Many cities globally are experiencing shortage in institutionalized resources, such as healthcare and eldercare facilities and manpower, to adequately care for the rapidly increasing elderly (aged 65 and above) population [1]. In Singapore, it is estimated that by 2030, one in every five persons - or roughly 900,000 persons - will be elderly [2]. An emerging paradigm that can potentially alleviate the reliance on institutionalized care is aging-in-place, where the elderly can continue to stay in her residential home independently, safely, and comfortably [3] and be in close contact with family and friends.

However, there is a worrisome upward trend of the proportion of one-person households comprising an elderly. If the current trajectory continues, there will be approximately 83,000 elderly who are staying alone by 2030 in Singapore. Hence, there is a need to rely on timely response by caregivers and volunteers in the community, i.e., *community eldercare*, to meet the day-to-day *safety* needs of these elderly. In the longer term, community eldercare to meet their *health* and *social* needs requires the reliable assessment of behavioral and clinical status across multiple interrelated domains (cognitive, social, physiological and environmental). This is challenging due to the complexity in detecting and identifying events that rarely or infrequently occur, as well as those that evolve slowly over time and lack a clear initial onset.

Fortunately, the maturing of sensing and communication technologies, as well as data science, is enabling the deployment of In-Home Internet-of-Things (IoT) solutions that can enable community eldercare through: (*i*) continuous monitoring of day-to-day activities of the elderly in real-time; and (*ii*) intelligent detection of anomalous events. However, the large-scale deployment of IoT solutions for community eldercare requires care centric and technology centric challenges to be addressed. Care centric issues can be summarized as follows:

- **C1** The receptiveness of both the elderly and the community caregivers towards technology is key for the successful adoption of IoT for community eldercare. Stakeholders who have not yet been exposed to technology are likely to be apprehensive on the usefulness of such technological solutions.
- **C2** A strong community support network is critical for community eldercare. This can be particularly challenging, in the absence of inherent 'neighborliness', and/or a mechanism to alert neighbors to tend to help requests from the elderly.
- **C3** Finally, a practical and robust care and response protocol must be in place to ensure that community caregivers are notified and respond to the elderly, in times of need, without ambiguity.

On the technology front, there are also a spectrum of challenges that are pertinent to the successful implementation of technology-enabled community eldercare:

- **T1** As systems can quickly become obsolete when incumbent technologies are replaced with newer and better ones, it is essential to design with modularity and extensibility in mind to adapt seamlessly to rapidly and continuously evolving technology.
- **T2** The system must be able to scale beyond circumscribed communities to thousands, and tens of thousands of homes, in a reliable manner.

T3 An in-home elderly monitoring system is unable to account for out-of-home activities that are undertaken by the elderly.

T4 As the elderly may host visitors from time to time, the system must be able to accurately identify the elderly of interest to establish her daily living patterns.

T5 The heterogeneity resulting from a lack of standards in IoT and/or smart home solutions leads to non-interoperability between the available devices and service offerings in the market, and inefficiencies in cost and system operations.

In this chapter, we focus on technology-centric challenges **T1** and **T2**, and share our experiences and lessons gleaned from ongoing project partnerships with a community eldercare ecosystem comprising government agencies, community caregiving organizations and technology providers, to evaluate the sustainability of technology-enabled aging-in-place from a holistic viewpoint. To complement the technological aspects, we conducted ethnographic studies on our elderly participants through a combination of participant observations and surveys. This enables a quantitative and qualitative understanding of how in-home IoT systems can better address their safety needs and enhance their overall quality of lives.

The rest of the chapter is organized as follows. In Section II, we present a survey of related work. Section III describes the applications in community eldercare and our deployments in more than 70 elderly homes in Singapore. In Section IV, we present the system architecture of our eldercare monitoring system. In Sections V, VI, VII and VIII, we elaborate on the challenges that we have faced in the deployment and lessons learned. We discuss ongoing and future work in Section IX.

2. Related Work

While the recent advances in IoT is making smart homes a reality, its widespread adoption and deployment remains elusive in aging-in-place applications. This is mainly due to the cumbersome use of technology by elderly unfamiliar with its use, perception of privacy invasion, and the lack of personalized and objective indicators of functional independence that determine the health and wellbeing of the elderly within their residential home environment.

As such, various global research initiatives in smart homes to support aging-in-place primarily focus on passive in-home monitoring without the need for active participation by the elderly [4, 5]. Such elderly monitoring infrastructure generally consists of sensing devices embedded in the environment, a communication system that relays the data, and computing systems that reason about it. Typical sensors used for passive monitoring include motion sensors, door contact sensors, Kinect depth sensors for gait assessment and fall detection, and hydraulic bed sensors. These unobtrusive systems can capture clinically significant Activities of Daily Living (ADLs) and instrumented Activities of Daily Living (iADLs) at home. However, the sample sizes are typically quite small, and most research focus on the investigation of models to analyze sensor data, measure daily functioning or determine and identify changes in ADL patterns, and less on its application in everyday life and clinical practice.

TigerPlace, a state-academic-private project, is a 54-apartment independent living facility in Columbia, Missouri, where individual apartments have been instrumented with inexpensive sensors since 2005, to monitor residents' movements. Beyond safety-oriented applications (i.e., sensing problems and alerting caregivers after the fact), researchers at the University of Missouri are devising ways to identify behavioral shifts that can alert caregivers to a potential problem [6].

Since 2004, the Oregon Center for Aging and Technology (ORCATECH) has begun research studies and pilot testing of the use of in-home technologies for health monitoring, intervention, and support of independent living on a population of 30 community-dwelling seniors [7]. In addition to passive monitoring using sensors, each participant receives a desktop computer and Internet broadband services, along with computer training based on their computer literacy. Subsequently, participants receive a weekly online health questionnaire about behaviors that may affect activity patterns as well as changes to the home environment (self-reporting). The

ORCATECH team first examines usability, feasibility, and reliability of the technologies and methods, before wider dissemination to the large-scale longitudinal community cohort study comprising participants from the Portland, Oregon metropolitan area.

The CSIRO Smarter Safer Homes (SSH) platform [8], comprising a sensor-based in-home monitoring system, a cloud computing server, and a client module with an iPad app, a family/carer portal and a clinical portal, has been piloted in 26 homes in Australia since 2013. A 12-month observational study in 17 homes in Armidale validated the usability and acceptability of the SSH platform, as well as the capacity to extract the fundamental domains of ADL. Three carers/nurses with a nursing care service (3 homes, Melbourne, 3-month, observational) reported in a study in 2014 that the SSH iPad App was simple and easy to use, and the presentation of ADL data can facilitate enhanced delivery of nursing service. A third study in 2015 with home care providers (6 homes, Sunshine Coast, 12-month, interventional) extended the features of SSH to include real-time monitoring, and demonstrated its ability to provide valuable insights to care providers.

In Singapore, there have been some recent smart home initiatives to meet the safety needs of the elderly. In 2013, 500 elderly residential homes were instrumented with an emergency help device, motion and door contact sensors, as part of a community-led initiative [9] in partnership with a community eldercare provider. In 2015, the Housing Development Board (HDB) completed the trial of a similar system with 12 flats [10], targeting the next-of-kin as the care responder.

A recent study [11] based on TigerPlace was conducted to identify deviations in daily routines preceding changes in health trajectory of older adults. Thus far, this is the only research work that highlights factors that affect reliability of sensor data while containing cost and unobtrusiveness of smart home monitoring for older adults, specifically, (*i*) sensor deployment to minimize dead zones while reducing overlap; (*ii*) size and aesthetic appeal of sensors; (*iii*) interference and power outages; and (*iv*) noise, errors, and missing data.

Our project SHINESeniors [12] is an inter-disciplinary research effort that studies the use of sensor-enabled homes and personalized home care technology to enable elderly Singaporeans who live alone to age-in-place through community eldercare. It represents a holistic study that builds on existing work to address (*i*) the immediate and personal safety needs of the elderly; (*ii*) the long term health and social needs of the elderly and (*iii*) the technology-centric and care-centric challenges for sustainable technology-enabled community eldercare. At the time of writing, more than 70 elderly residential homes have been instrumented with multi-modal sensors for almost 2 years.

3. ELDERCARE APPLICATIONS AND DEPLOYMENTS

We first present the target community eldercare applications that will enable elderly living alone to age-in-place independently and safely. We then enumerate their key requirements, and describe our IoT deployments in more than 70 elderly homes in Singapore.

The IoT deployments comprise devices in the home of each elderly as well as end-user devices (such as smart phones) for community caregivers. In addition, we presuppose the following: (*i*) assignment of elderly to caregivers; (*ii*) association of in-home devices with elderly; (*iii*) association of an end-user device with each caregiver; and (*iv*) storage of relevant contact information of the elderly and caregivers.

Key Applications and Their Requirements

Figure 1 illustrates a typical community eldercare scenario, wherein community caregivers are alerted every time events of interest (i.e., emergency alert activation, prolonged inactivity, and medication non-adherence) occur on the elderly under their care. In the following, we discuss the functional and performance requirements of three key applications that corresponds to the three events of interest shown in Figure 1.

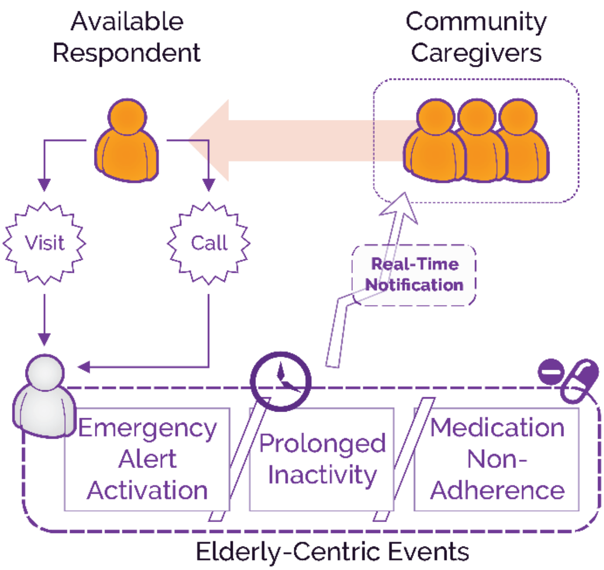

Figure 1. Application use cases for community eldercare.

Emergency Alert

An elderly living alone can be provided with an ‘emergency help device’ that she can easily activate (for instance, by pressing a button) to call for assistance whenever she encounters an emergency at home. When the device is activated, an alert is sent immediately to each of her assigned community caregivers, who can then respond and provide timely assistance.

1) Functional Requirements

The first functional requirement of the emergency alert application is that an alert message must be delivered to the end-user devices of the assigned community caregivers, whenever the emergency help device is activated. The alert message must indicate the identity of the associated elderly, timestamp of the event, and contact information of both the elderly and the caregivers. The second functional requirement of the application is that is must enable caregivers to signify their intent to attend to the elderly. When a caregiver responds, the system must indicate to the elderly that help is on the way.

2) Performance Requirements

The emergency alert application has stringent performance requirements. In particular, all alert messages must be delivered *reliably* (i.e., no missed detection) and in *real-time* (i.e., with minimal latency). The same set of requirements applies to the response from the caregivers. As the elderly may trigger the emergency help device at any time of the day, the system must have high availability.

Prolonged Inactivity Detection

Despite its potential to offer timely assistance to the elderly in distress, the unfortunate reality is that the emergency help device is typically hung on the wall in the living room, or near the bedside, instead of being worn by the elderly. Consequently, the device is often not within the elderly's reach when they need help. With prolonged inactivity detection, alerts can be sent to the community caregivers whenever the duration of non-movement exceeds a pre-determined inactivity threshold. This could indicate that the elderly has been motionless for a while and may require assistance from the caregivers, and can complement the emergency alert application (which requires a more pro-active approach to request for assistance).

1) Functional Requirements

Prolonged inactivity detection requires: (*i*) installation of motion sensors around the house to detect movements (and hence non-movements); and (*ii*) algorithm(s) to compute personalized inactivity thresholds for each elderly, based on her daily activity patterns. When the duration of non-movement in the house exceeds the inactivity threshold, an alert message must be delivered to the end-user devices of the assigned community caregivers. The alert message should indicate the identity of the elderly, timestamp of the event, and relevant contact information of both the elderly and the caregivers. Similar to the emergency alert application, the caregivers must also be able to indicate their intent to attend to the elderly, and the elderly must also be made aware that help is on the way.

2) Performance Requirements

The system must have high reliability, low latency and high availability. The sensing coverage, sensitivity and accuracy of the sensors are also important in order to minimize: (*i*) false alarms, which can arise if the motion sensors do not detect motion when it is present and thus trigger inactivity alerts; and (*ii*) missed detections, which can take place if the motion sensor detects motion when there is none.

Medication Adherence Monitoring

The elderly population is generally more susceptible to adverse health complications that may arise from medication non-adherence. By monitoring their medication intake to identify non-adherence, alerts can be triggered to the respective caregivers to provide the appropriate levels of intervention and minimize further health deterioration in the elderly.

1) Functional Requirements

Each elderly has a prescribed medication routine, such as the type and timing of medication to be consumed. The system should identify the actual frequency and timing during which medication is consumed - and compare such data with the respective prescription. If the elderly misses her medication according to some predefined, personalized rule (e.g., misses medication for x consecutive days, or any x days within the past week), the caregivers should be notified accordingly. Interventions undertaken by the caregivers should then be captured into the system for subsequent analysis.

2) Performance Requirements

The system must be able to accurately identify when the elderly has lapses in her medication intake. Depending on the personalized alert rules that are being set by the caregivers, the performance requirements may vary. For instance, if an elderly has stringent medication intake requirements, alerts will have to be delivered to the caregivers as soon as the dosage is missed. In contrast, the alerts for other elderly who are generally healthier, can be delivered to the caregivers on a weekly or monthly basis.

Deployments

Our deployment of IoT systems for community eldercare thus far comprises five blocks, as summarized in Table I:

1. 40 elderly in Estate A serviced by caregiver C_1, with Vendor V_1's system for emergency alert, and prolonged inactivity detection;
2. 10 elderly in Estate A serviced by caregiver C_1, with Vendor V_1's system for emergency alert and prolonged inactivity detection and a research prototype for medication adherence monitoring;
3. 14 elderly in Estate B serviced by caregiver C_2, with a research prototype for medication adherence monitoring;
4. 10 elderly in Estate B serviced by caregiver C_3, with Vendor V_2's system for emergency alert and prolonged inactivity detection; and
5. 1 elderly in Estate B serviced by caregivers C_2 and C_3, with Vendor V_2's system for emergency alert and prolonged inactivity and a research prototype for medication adherence monitoring.

Table 1. Our IoT deployments for community eldercare, where n_i refers to the number of elderly in block i of the deployment

Application	Estate A (Vendor V_1, research prototype*)		Estate B (Vendor V_2, research prototype*)		
	n_1 = 40	n_2 = 10	n_3 = 14	n_4 = 10	n_5 = 1
Emergency Alert	•	•		•	•
Prolonged Inactivity Detection	•	•		•	•
Medication Adherence Monitoring*		•	•		•

4. SYSTEM ARCHITECTURE

In this section, we describe the system architecture that underpins the various IoT deployments for community eldercare, which we have completed thus far. As depicted in Figure 2, the current deployed system comprises (*i*) in-home monitoring devices; (*ii*) backend and user interfaces for community care providers.

In-Home Monitoring Devices

To address the functional requirements of the eldercare applications presented in Section III, the following hardware components are installed in the elderly's home.

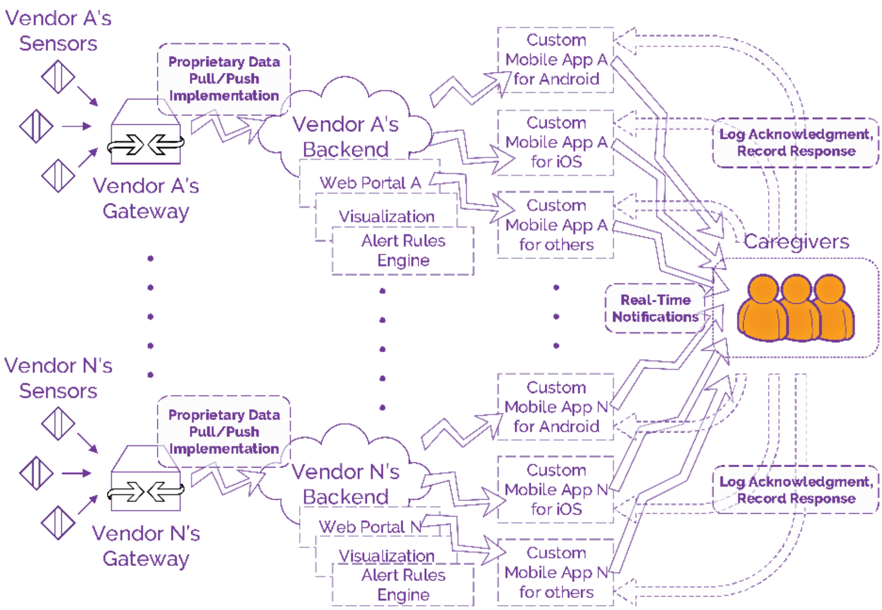

Figure 2. Architecture of current IoT-enabled community eldercare system.

1. Emergency Alert Device

The device, usually in the form of a button, enables the elderly to explicitly call for help from her caregivers while she is at home. The device must be light, portable, and not require frequent recharging or replacement of the battery.

2. Motion Sensors

Battery-powered motion sensors are installed in several locations of the elderly's home, to monitor activity (and hence inactivity). These sensors must be positioned and oriented to ensure maximum sensing coverage.

3. Door Contact Sensors

Door contact sensors are typically battery-powered and based on reed switch technology. They are installed on all entry/exit points in the home. Together with data from the motion sensors, algorithms can be applied to determine if prolonged inactivity occurs due to one of the following scenarios: (*i*) elderly is out of the home, and hence alerts should not be triggered; or (*ii*) elderly is motionless at home for more than a pre-specified threshold, and hence alerts should be triggered to the community caregivers.

4. Medication Box

Each elderly whose medication adherence is being monitored will be given a battery-powered sensor-enabled medication box, in which they can place their medication. The medication box will track the inferred medication intake of the elderly, through usage of the box - for instance, when the box is opened or closed.

5. Gateway

Each IoT-instrumented elderly home will be equipped with a mains-powered gateway that: (*i*) collects data from all the other sensor devices via short-range low-power wireless communications such as Z-Wave; (*ii*) performs lightweight computing; and (*iii*) transmits the sensor data to the backend server(s) via cellular communications.

Backend and User Interfaces

The backend ingests, stores and processes sensor data from the gateway. To enable community caregivers to monitor the elderly in their care and respond to events such as emergency, prolonged inactivity, and/or missed medication, key actionable information is provided to them via user-friendly interfaces such as mobile applications and/or dashboards.

5. Lessons Common to All Applications

Lesson #1: Sensing and Connectivity

The Internet of Things (IoT) thrives on open standards, protocols, and architectures for interoperability and communication between things.

There are two key approaches that IoT solution providers adopt: (i) fully-proprietary, which includes building all sensors in-house and having them communicate via a proprietary protocol; or (ii) integrative approach, which includes getting commercial off-the-shelf (COTS) sensors based on interoperable standards from sensor suppliers, and providing a gateway to integrate the sensors with the rest of the system.

Our experience with several vendors suggests that the integrative approach works better, due to the following reasons:

1. COTS sensors have a larger user base; this is advantageous as: (*i*) product reviews are more easily available (for instance, on Amazon.com), thus reducing the risk of purchasing faulty or unreliable products; and (*ii*) product reviews are channeled back to the sensor suppliers, who can then improve their products.
2. The vendor's gateway is potentially interoperable with a larger number of devices. This eases integration efforts with other devices, shortens time-to-market, and provides end-users with more choices to meet their needs.
3. Users are not locked-in to a particular vendor, as there are: (*i*) multiple sensor suppliers that can provide competing types of multi-modal sensors (e.g., motion and door contact sensors); and (*ii*) multiple vendors that can integrate these sensors with their own

products. This results in a competitive and innovative environment, whereby end-users have the freedom to select sensor suppliers and vendors that can best meet their needs.

Lesson #2: Data Storage and Integration

Due to the dynamic and diverse data requirements of eldercare applications and deployments, it can be especially challenging to design an all-encompassing data model. Based on our experiences, storage of data in different database types can thus yield the most efficiency and flexibility. Highly structured data and unstructured data can be stored in SQL-type and NoSQL-type databases, respectively. These data can then be transformed to a common data format prior to further processing and analysis by data scientists.

In typical IoT applications for community eldercare, current data (within the last few days) is typically accessed more frequently, and must be separated from historical data. This ensures that another application that is accessing large volumes of historical data will not penalize the performance of applications that are accessing current data. Furthermore, regular and automated data housekeeping (i.e., moving of older database entries to another database that stores historical data) is required to: (*i*) ensure quick database responses to queries in current datasets; and (*ii*) ease system management.

Data integration refers to the combination of heterogeneous data that is residing at different sources, to provide the user with a unified view of such data [13]. Our experience have shown that it is not efficient to move data to a single location. Rather, the availability of a universal interface or API for accessing data (that is possibly stored in different locations) is sufficient to perform data analytics.

Lesson #3: Alert, Escalation and Response Protocols for Many-to-Many Eldercare Model

In the conventional eldercare model, the respondent is a single caregiver, i.e., the Next-Of-Kin (NOK). In contrast, the community eldercare model involves a many-to-many relationship, whereby multiple caregivers take care of many elderly in the community. As such, each alert event from a single elderly is delivered to multiple caregivers at the same time through their mobile phones.

Alert delivery is critical for timely response by caregivers, especially to emergency situations and prolonged inactivity. As delayed or non-delivery can potentially threaten the safety of the elderly, the system must provide the highest Quality of Service (QoS) possible in terms of both latency and reliability.

However, it is possible that the assigned caregivers do not receive the notifications immediately; this can happen due to various factors, such as poor cellular coverage on the caregiver's mobile phone, or if the caregiver does not notice the notifications on the mobile phone. A robust escalation protocol must therefore be in place, such that the alerts are delivered to the next tier of available caregivers, if the current tier of caregivers are unable to provide prompt attention and response to the elderly.

Following on, an appropriate response protocol must be designed and implemented, such that: (*i*) only one caregiver can respond to each alert (even though multiple caregivers may receive the same alert); and (*ii*) all assigned and notified caregivers receive the update status of each alert.

Lesson #4: User Interfaces

The popularity of mobile devices necessitates the development of web interfaces using responsive design techniques. This reduces developmental efforts, as the same interface can be utilized across various screen sizes. The advent of Chrome Web Push [14] enables push notifications to be sent through the web browser, instead of requiring the end user to install another mobile application on the mobile phone.

Most vendors that provide eldercare solutions have user interfaces designed for the one-to-one NOK care model, whereby each elderly is cared for by one caregiver. However, in community care, multiple caregivers are typically assigned to care for multiple elderly (many-to-many). The user interface thus needs to be designed to allow caregivers to configure and view data of multiple elderly at the same time.

Lesson #5: Network Management

The large-scale nature of IoT systems for community eldercare necessitates careful consideration of the network management aspects. While great engineers take pride and responsibility in designing systems that work continuously (over months or even years), it is reasonable to expect consumer-grade electronics and software to fail occasionally. Hence, each component (both hardware and software) of the IoT eldercare system requires meticulous and modular system and performance monitoring, for fault detection, diagnosis and rectifications whenever necessary.

In our deployments, we are notified within 30 minutes, and use Slack [15] to transmit system-level alerts to the system administrators, whenever any system component experiences faults - such as when the battery of a sensor falls below a percentage threshold, gateway goes offline, or a particular process in the backend system becomes unavailable.

To address the issues of fault, we have to balance the idealism of the developers: "*I want to address the root cause of every problem and provide a solution.*", and the realistic demands of operationalization: "*Things fail and we can accept quick fixes or workarounds, as long as they can improve the system uptime.*"

Since getting to the root cause takes time, we implement temporary workarounds such as restarting the gateway periodically to make the system usable and improve uptime. The root cause can be fixed subsequently if the alerts include a comprehensive list of components that might have failed, and suggest the causes of failure: *was the internet connection down? Was the gateway leaking memory etc.?*

Due to the evolution in IoT technologies, it is inevitable that firmware/software needs to be updated. The use of Over the Air (OTA) programming is desirable as it can minimize the number of maintenance visits to the elderly's home.

6. Lessons Specific to Emergency Help Device

Emergency help devices for eldercare applications can come in the form of a pull cord, wearable wristwatch, or portable panic button - with the latter being the most pervasive of such devices. Based on our experiences, the ideal emergency help device should feature the following characteristics:

1. Right form factor, to spot, hold and carry easily. Devices that are too small can be lost easily, whereas devices that are too large are cumbersome and non-portable.
2. Right sensitivity, such that the elderly can easily activate the device to call for help. However, the device cannot be overly sensitive, such that it is triggered too easily and generates excessive false alarms to the caregivers.
3. Robust (water-proof and shock-proof) casing, such that the elderly does not have to worry about damaging the device as she brings it around with her in the house, or even when she drops it accidentally.
4. Long lifetime and availability, such that the device can operate for as long as possible, without the need for frequent recharging or changing of batteries.
5. Provides feedback to the elderly to confirm that her call for help has been acknowledged by the system, such that the elderly feels assured that help is on the way.
6. Provides remote tracking and update of the device status (such as the battery level), such that the devices do not have to be

periodically and manually tested for their operationality, which can impose additional inconvenience for both the caregivers and the elderly.

7. LESSONS SPECIFIC TO PROLONGED INACTIVITY

Lesson #1: Design and Placement of Motion Sensors

Prolonged inactivity detection requires the installation of motion in each part of the elderly's home, and door contact sensor on the main door. Some key considerations in the selection and/or design of these sensors include:

1. Sensors should have a small form factor and appear aesthetically pleasing. The use of neutral colors (such as white) for sensor casings accents their un-obtrusiveness, and allows the elderly to carry on her daily activities without being hindered by the presence of additional devices in the home.
2. Many motion sensors have LED lights that are triggered, whenever motion is detected. As this can be quite distracting and disruptive to sleep for some of the elderly, a tape can be applied to block the LED lights.

To minimize both accidental and deliberate tampering, motion sensors should be installed at locations that are not easily accessible. However, care should be taken to ensure that their placement does not affect the sensing coverage and communication with to the gateway.

Lesson #2: Personalized and Dynamic Thresholds

In prolonged inactivity detection, an alert is triggered if there is no motion in all parts of the home for a pre-specified `inactivity threshold'. In community eldercare, the setting of the inactivity threshold is of particular importance, as a setting that is: (*i*) too short may generate excessive false alarms (for instance, when the elderly is idle - during periods of nap, sleep or rest) for the caregivers, who may become indifferent to such alerts; and (*ii*) too long will result in a long delay being incurred before help is being rendered to the elderly, in the case of true emergencies.

To optimize the tradeoff between false alarm rate and detection latency, we advocate (and have experience with) the use of personalized and dynamic inactivity thresholds, according to the unique lifestyle of each elderly:

1. We can exploit the elderly's dwell times to reduce inactivity thresholds in locations where she does not typically stay for long durations (i.e., bathroom and kitchen). In a simulation study using real historical data, we have used location dwell times in a scheme called ATDT to significantly reduce the detection latency of emergency events occurring in these locations while maintaining the false alarm rate [16].
2. Elderly tend to be more active at home during their waking hours, and less active during the night time when they are asleep. Historical sensor data of the elderly can be mined to derive her individual sleep cycle, from which the appropriate inactivity threshold during her awake and asleep hours can be determined.
3. The daily living patterns of the elderly may evolve over time, due to factors such as changes in physical health or living arrangements. It is thus necessary to adapt the inactivity threshold of the elderly on a regular basis (e.g., every month), based on her prevailing conditions.

Prolonged inactivity can also take place, when the elderly is out of her home. To minimize the likelihood that false alarms are generated due to prolonged inactivity when there is no one at home, we make use of the door contact sensor data in tandem with an algorithm that detects the occupancy status of the home (i.e., empty or occupied). If prolonged inactivity is detected when the home is determined to be occupied, an alert will be triggered to the community caregivers; conversely, no alerts will be triggered when there is prolonged inactivity when the home is empty.

Lesson #3: Robust Prolonged Inactivity Detection Algorithm

Prolonged inactivity detection is highly dependent on both the: (*i*) motion sensors, to determine if there is no motion or activity in all parts of the home for a pre-specified inactivity threshold; and (*ii*) door contact sensor, to determine if the elderly has entered or left the home (based on the opening and/or closing of the main entrance to the home).

However, sensor readings from the COTS motion and door contact sensors are prone to intermittent noise and errors. Some of the most common sources of sensor errors that we have encountered in our deployments are: (*i*) random motion being detected at a particular location of the home even when there is no one at home, which can lead to subsequent activation of the prolonged inactivity alert; and (*ii*) missing door contact events, which can lead to false alarms and missed detection of the prolonged inactivity alerts. Subsequently, the inactivity detection algorithm must be designed to be robust to such errors, in order to minimize such false alarms and missed detection of prolonged inactivity detection.

8. LESSONS SPECIFIC TO MEDICATION ADHERENCE

Non-adherence to medication is a prevalent issue that contributes to the deteriorating health of the elderly. Survey results from one of our earlier studies [17] show that more than 75% of the elderly suffer from more than 3 chronic illnesses, and more than 80% consume medication as part of their daily lives. As part of community eldercare, it is thus important to monitor the medication consumption habits of the elderly, so that timely reminders can be sent to the elderly as necessary.

Lesson #1: Medication Box Design

Based on our observations of and interactions with the elderly in our studies, we have identified two key insights with respect to medication box designs.

1. In Singapore, as hospitals often dispense medication in 3-monthly dosages, most elderly will have a large stock of medication in their possessions. While some will store them in a single large storage container/bag, others may prefer to pack into batches of monthly doses, according to individual prescription types, or based on the prescribed timing of the dosage (e.g., morning, afternoon and evening). Hence, the medication box needs to cater to these individual deep-rooted habits for sustained use.
2. Depending on their demographics and technical literacy, different elderly will have varying receptiveness towards the use of a 'smart' medication box. The medication box should be simple in design and easy to use, without complicated procedures to fill up or dispense medication.

Consequently, there is no 'one-size-fits-all' medication box design that can cater to the idiosyncrasies of each elderly. In our projects, we customize the medication box according to the needs and preferences of each elderly, by retrofitting off-the-shelf boxes with sensors to detect the frequency and timing of medication box usage. This serves as a proxy for the inferred medication intake of each elderly.

Lesson #2: Personalized Alert Delivery

Each elderly has different medication conditions and medication prescriptions. For instance, some elderly may have two medication intake dosages daily, while others have more. The system must therefore provide a user-friendly interface to input the expected medication timings for each elderly.

Furthermore, in community caregiver setting, it is unrealistic for the caregiver to continuously receive alerts when the elderly forgets his/her medication. Elderly with more severe chronic illnesses, such as Parkinson's, may require more regular medication intake - whereas it may be acceptable for other elderly to have a certain number of missed medication doses before the caregivers are being notified.

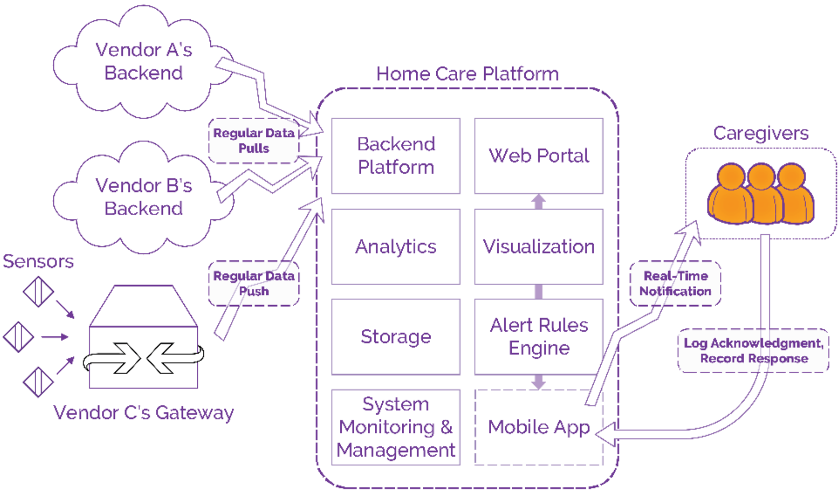

Figure 3. Unified architecture of IoT-enabled community eldercare system.

9. Ongoing and Future Work

Reflecting upon the lessons learnt from our IoT deployments for community eldercare, the idea of a unifying IoT platform to overcome some of the challenges faced was conceived. Figure 3 illustrates how this unifying Home Care Platform (HCP) contributes to an enhanced system architecture. In the following, we describe the key differentiators of the HCP as follows.

Integration with External Systems

The HCP is designed to integrate, assimilate and accommodate multiple and different external enterprise systems, while providing extensible and versatile interfaces to exchange data, communicate, and work together in an automated manner. For instance, the HCP is currently able to ingest data from sensor systems provided by vendors V_1 and V_2 in our deployments to provide a unified interface to the caregivers and system administrators to view the data. These user interfaces can also be used to capture survey responses from the elderly, as well as ground observations.

In the future, the HCP will also seamlessly integrate with other structured data as well as unstructured data such as survey responses and ground observations. It will also be able to integrate with other external systems - such as Customer Relationship Management systems that are typically used by caregiving organizations to log casework, medical history, and other pertinent information about the elderly whom they serve. Eventually, HCP is envisaged to be integral part of a larger ecosystem, exchanging data with other systems - such as the National Electronic Health Records - in the whole spectrum of care.

Alert Rules Engine

The alert rules engine is responsible for transmitting alerts and updates reliably to the community caregivers, to notify them of the elderly who require their attention and response. Caregiver responses (such as comments or actions undertaken) to the triggered alerts are tracked; such information can be used for subsequent review and analysis of the elderly's wellbeing. Escalation protocols are put in place, such that alerts are delivered to the next tier of community caregivers, if the current tier of caregivers are unable to provide responses within a specified interval of time. Relevant authorities can also be automatically notified, if the alerts are deemed sufficiently critical. In addition, the alert rules engine empowers community caregivers with the responsibility and flexibility to specify alert rules and escalation protocols, which enables them to provide better care for the elderly.

Multi-Modal Data Analytics

Data fusion and multi-modal data analytics will enable the HCP to provide new applications and services that can enhance the provision of care to the elderly. Features of interest can be extracted from raw sensor readings, and by correlating them with the various wellbeing indices (e.g., social isolation score, depression score, etc.), feature sets that can predict the mental and emotional wellbeing of the elderly can be identified and incorporated into the HCP's analytics core.

System Monitoring and Management

The HCP is designed to provide device and network management tools to monitor and manage the IoT eldercare system to allow it to scale and be replicated across a large number of elderly homes, for effective care and intervention by community caregivers. At the time of writing, the HCP can already display the battery levels of sensors. In the future, it will be extended to include downtime alerts for sensors, gateway status, predictive maintenance, and battery replacement schedules.

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