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Quantifying Activity Levels of Community-Dwelling Seniors through Beacon Monitoring

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***Abstract*—The ageing population is rapidly increasing, both in Singapore and worldwide. Due to the shortage of healthcare professionals and institutionalized care, there is a pertinent need for seniors to age-in-place - safely and in the familiarity of their neighborhoods. In addition, changing family structures and rising divorce rates, coupled with the desire for more personal space and independence, have resulted in a significant proportion of seniors who live alone at home.**

In this paper, we describe a scalable and low-cost monitoring system that can help to identify community-dwelling seniors who are at risk of social isolation and/or frailty. This is achieved by monitoring the seniors' activity levels (which are computed based on the timings and durations that seniors spend in their residential homes), through the use of Bluetooth beacons and the seniors' smartphones. The system has been implemented and deployed in 81 residential homes, over a period of 3 weeks. Preliminary results show that the system can provide a low-cost and efficient way of providing caregivers with insights on each senior's well-being, based on his/her activity levels.

***Index Terms*—ageing-in-place, social isolation, frailty, beacons, sensor monitoring, activity levels, non-intrusive.**

I. Introduction

The ageing issue in Singapore has become increasingly prevalent in recent years, with the total number of seniors projected to grow to 900,000 by 2030 [4]. Rising healthcare costs, shortage of healthcare professionals, and limited institutionalized care facilities have resulted in the need for these senior Singaporeans to *age-in-place*, in the comfort and familiarity of their neighborhoods. Changing family structures and living preferences have also led to the upward trend of seniors who live alone at home.

The narrative for ageing-in-place has primarily focused on providing accessible care services within the community, and creating safe environments for seniors when they are at home. In particular, the latter is achieved by leveraging Internet of Things (IoT) technologies which can provide remote monitoring of seniors, and subsequently informing caregivers in a timely manner whenever help is required. In Project SHINESeniors (Smart Homes and Intelligent Neighbors to Enable Seniors) [8], multi-modal IoT devices are installed in the residential homes of seniors; alerts are triggered to the community caregivers whenever anomalous events (such as prolonged inactivity at home or prolonged inactivity at the main door) are detected. As a secondary objective, the same IoT devices can also be used to classify seniors in terms of their wellbeing, for instance - by detecting seniors who are depressed [10], [11], at risk of social isolation [9] or at risk of frailty [12]. However, the cost of the full suite of multi-modal IoT devices is prohibitive for large-scale, city-wide deployments - both in terms of capital expenditure and operating expenditure (for instance, incurred through sensor/system maintenance). Furthermore, these systems have often been designed and implemented with the assumption that the seniors do not own smartphones.

In this paper, we propose a scalable and low-cost monitoring system that can help to identify community-dwelling seniors who are at risk of social isolation and/or frailty. In prior studies [9], [10], [12], among various sensor-derived features, it has been shown that the average *going out duration* of the seniors is correlated with the risk of depression, social isolation and/or frailty. Instead of deploying the costly suite of multi-modal sensors in the seniors' home, the timings and durations that seniors spend indoors (at home) and outdoors (outside of home) can be measured through a simple and low-cost alternative - through the dual use of Bluetooth beacons that are placed at home, and the seniors' smartphones. Such an approach is viable, as seniors in Singapore have high smartphone penetration rates. Approximately 31% of senior Singaporeans aged 60 and above surf the web regularly via their smartphones [6]; among the younger seniors aged 50 to 59, this percentage increases to 75%.

The *activity level* of each senior can be derived based on the acquired sensor data. Seniors with low activity levels are generally at higher risk of poor wellbeing, which can lead to depression, social isolation and frailty. These seniors can be flagged out to their respective caregivers, who can then take appropriate interventions to improve the activity/engagement levels of the at-risk seniors.

The system has been implemented and deployed in the residential homes of 81 senior Singaporeans, over a period of 3 weeks. Preliminary results indicate that the system can provide a low-cost and efficient way of providing caregivers with insights on each senior's well-being, based on his/her activity levels. The system can also identify anomalies in the senior's activity levels, as well as provide a benchmark of each senior's activity levels as compared to the cohort average.

The rest of this paper is organized as follows: Section II describes related work on real life deployment of sensor monitoring systems for community dwelling seniors. Section III describes our system design and architecture. Evaluation

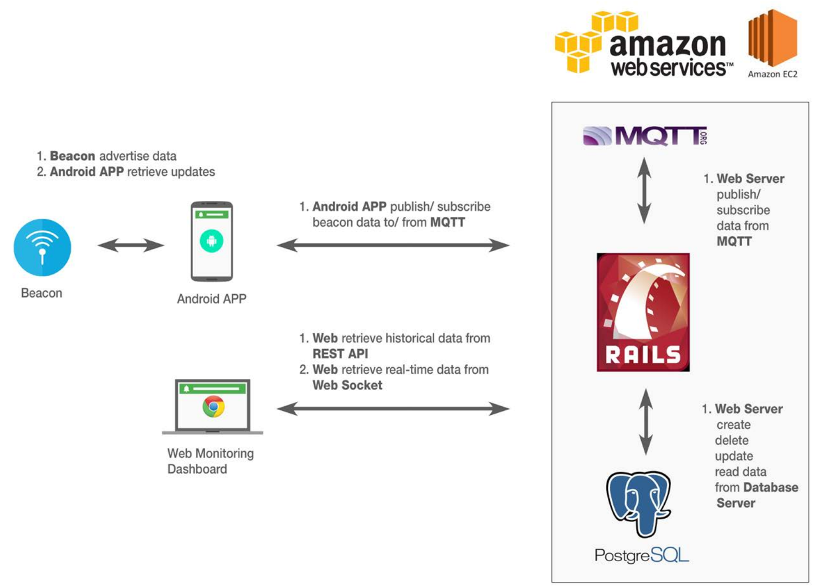

Fig. 1. System overview.

results are presented in Section IV. We conclude with discussions and directions for future work in Section V.

II. Related Work

In recent years, there has been multiple efforts that study the use of smart home technologies to enable seniors to age-in-place. In many of these studies, a full suite of multi-modal sensors (comprising passive infrared motion sensors, door contact sensors and emergency push buttons) is placed in each senior's home, to monitor their daily living patterns, and to make inferences about their wellbeing [8]. However, these systems are often costly, and may require high system maintenance or support.

In another observational pilot study led by the National University Health System (NUHS) in Singapore, sensor-derived features are used to distinguish between seniors living alone and clinically assessed with MCI, versus those who are cognitively healthy (HC). The primary hypothesis that continuous and non-continuous data obtained from a multitude of low-cost sensors (including fixed sensors as well as Bluetooth beacons) over two months will differ between both groups, is evaluated over seven blocks of 48 seniors over 18 months. Preliminary analysis [14], [15] indicates differences in sensor-obtained activity patterns between the HC and MCI groups. In addition, qualitative feedback from research participants are positive, and there is enthusiasm for the system to be fine-tuned to support more seniors living alone.

City4Age [13], a European project funded under the Horizon 2020 framework programme for research and innovation, focuses on the use of smart city data to support active and healthy ageing among seniors. In particular, data from in-home sensors, smartphones and wearables will be used to capture the lifestyle of seniors living in cities, so as to detect signs of frailty or mild cognitive impairment (MCI). Subsequently, intervention plans will be developed to stimulate improvement in the quality of life of individuals, by interacting with them through mobile phones, TV displays, home robots or messaging devices. Although smart city data is being collected in six cities (Lecce, Madrid, Montpellier, Athens, Birmingham and Singapore), the data has yet to be verified and assessed by the domain experts (mainly geriatricians).

Our proposed work is motivated by the fact that while the use of multiple sensors in an in-home monitoring system can provide rich contextual information about each senior's wellbeing, such systems are often costly and thus prohibitive for large-scale, city-wide deployments. As such, we focus on the use of alternative monitoring solutions that are low cost, and can sufficiently quantify the activity levels of community-dwelling seniors.

III. System Design and Architecture

A. Overview

We first enumerate some design considerations for the proposed system:

1) **Low cost**: The system should be low-cost, both in terms of capital expenditure, and operating expenses; this can potentially be achieved by ensuring that the system comprises only the minimal set of devices/sensors that are required for the monitoring purposes.
2) **Smartphone penetration**: Existing literature often make the assumption that seniors do not own/carry smartphones. However, a significant proportion of the younger seniors in Singapore [6] are tech-savvy, and use smartphones on a regular basis.
3) **Low power consumption**: To minimize system maintenance efforts, as well as reduce the barrier of adoption

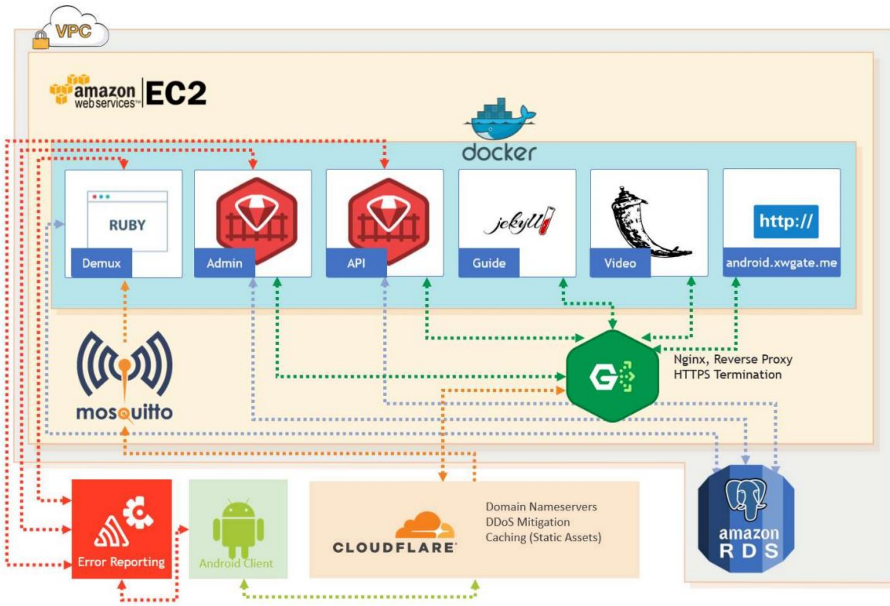

Fig. 2. Detailed backend architecture.

by seniors, each system component should incur low power consumption.

4) **Non-intrusive**: The system should be non-intrusive, and require little or no user interactions.

Based on our design considerations, the proposed system to identify the activity levels of community-dwelling seniors through beacon monitoring is achieved through the dual use of Bluetooth Low Energy (BLE) beacons, and the smartphones of the seniors. Beacons are low-cost devices - often in the range of USD5 to USD20 each - that work by periodically broadcasting wireless signals using the BLE protocol [3]. If this signal is detected by a nearby receiver, then it indicates that the beacon and the receiver are within proximity of each other. Conversely, if the receiver does not receive any signals from an arbitrary beacon, then it implies that the receiver and the beacon are not within the proximity of each other.

A beacon is placed in the residential home of each senior to be monitored. A mobile application is then installed on the senior's smartphone. The mobile application runs in the background, and is intended to be non-intrusive - such that there is no need for the senior to interact with the application. Whenever the senior's smartphone is within the range of the beacon (which is placed at home), it is inferred that the senior is indoors. If the senior's smartphone does not receive signals from the beacon, then it can be inferred that the senior is outdoors. We can thus quantify the activity levels of each senior based on the inferred indoor/outdoor activity data, and analyze these activity patterns to draw insights on the wellbeing and risk levels of the senior.

B. System Architecture

The overall system architecture is illustrated in Figure 1, and constitutes following key components:

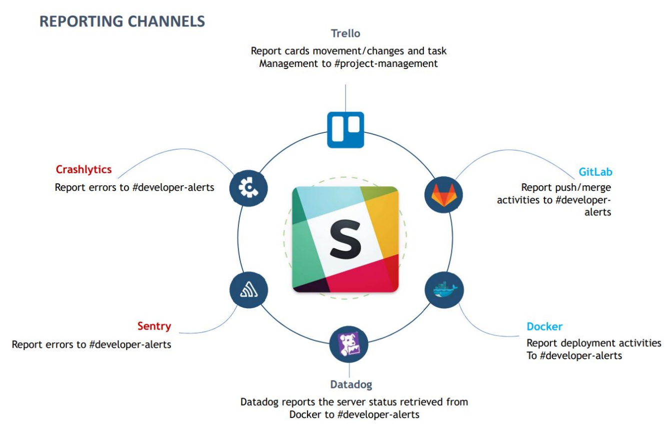

Fig. 3. System monitoring through Slack [2].

1) Internet of Things (IoT) Device Frontend: The IoT device frontend comprises BLE beacons that are placed in the residential homes of each senior, and a passive (Android) mobile application that is installed on the senior's smartphone. The mobile application runs passively in the background, and does not require any human inputs or interactions. It listens for wireless signals that are broadcasted by the corresponding beacon that is placed in the senior's home, and publishes data to the backend server via the MQ Telemetry Transport (MQTT) protocol [1]. MQTT is used as it is a lightweight protocol that incurs little overheads and consumes little energy consumption.

2) Backend Server: The backend server resides on the Amazon cloud service, and comprises of: (i) a MQTT subscriber that listens for data messages that are published by the mobile application that is installed on the senior's smartphone;

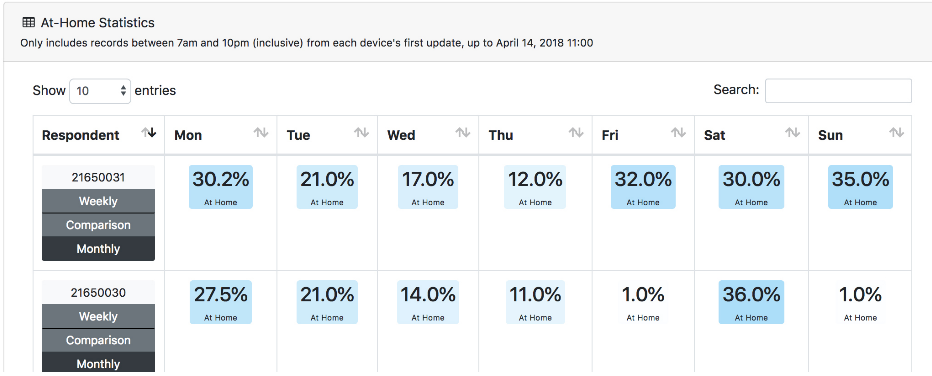

Fig. 4. Aggregate weekly at-home (indoor) statistics.

(ii) a web-application that is implemented using the Ruby on Rails web framework, and which provides data access via Application Programming Interfaces (APIs); and (iii) a PostgreSQL database that stores all the acquired sensor and system monitoring data. The detailed backend server architecture is illustrated in Figure 2.

3) Web Monitoring Dashboard: The web dashboard provides both administrative functions (such as IoT device management) and data visualization functions for caregivers to analyze and draw insights about each senior's activity levels, both in real-time as well as over longitudinal periods of time. The dashboard can also be configured to trigger customized alerts to caregivers - for instance, when the senior is observed to have not ventured outdoors for a pre-specified time threshold. This will allow caregivers to provide timely assistance and interventions to the seniors, to enhance care and improve the senior's wellbeing.

4) System Monitoring Framework: To ensure that the monitoring system is reliable and highly available, a comprehensive system monitoring framework that uses various off-the-shelf tools is put into place, as shown in Figure 3. As part of the monitoring framework, system alerts are generated and triggered to Slack [2] (a collaborative enterprise-level messaging system) whenever any of the system components (such as beacons, mobile application on the seniors' smartphones, and backend services) exhibit anomalies. This ensures that any system fault can be quickly rectified by the system administrators, as soon as such an event occurs.

C. Energy Efficiency Optimization of Mobile Application

The mobile application runs passively in the background of the smartphone, and is designed with energy-efficient techniques to enable the senior to use his/her smartphone as per his/her typical routine, with minimal impact on the battery lifespan of the smartphone.

The beacon that is placed at the senior's home is expected to broadcast wireless signals at every 1 second interval. To minimize the energy expenditure of the smartphone, the mobile application explicitly turns on the Bluetooth radio interface at every $t_{interval}$ time period, to scan for nearby beacons over a pre-specified duration of time t_{scan}. The Bluetooth radio interface is then switched off whenever the beacon is found, or at the end of the t_{scan} period.

Algorithm 1: Energy-efficient optimization on smartphone application

```
while TRUE do
    turn on Bluetooth interface
    scan for beacon at senior's home
    if beacon found or Bluetooth interface has been
      turned on for t_scan duration then
        turn off Bluetooth interface
    end
    publish data to backend via MQTT
    wait for t_interval duration
end
```

In addition, the mobile application periodically transmits data to the backend server at every $t_{interval}$ time period, to indicate whether it is within the proximity of the corresponding beacon during the previous time period. This data packet also serves as a keepalive message, to indicate to the system that the mobile application is up and running.

A summary of the energy efficiency optimization algorithm of the mobile application is summarized in Algorithm 1. We have used the values of $t_{scan} = 10s$ and $t_{interval} = 15\,\text{min}$ in our studies. While smaller values of t_{scan} and $t_{interval}$ can improve the accuracy of activity level detection, this can lead to higher battery expenditure of the smartphones, and thereby causing inconveniences to the seniors.

IV. Evaluation

Our low-cost beacon monitoring system to quantify the activity levels of community-dwelling seniors has been deployed with more than 81 senior participants, over a period of more than 17 weeks. Our participants have an average age of approximately 50 years old; we believe that the insights and learnings gathered from this study can be similarly applied to the seniors who are above 50 years of age. In the following, we present some preliminary analysis and insights about the participants' activity patterns.

Fig. 5. Detailed at-home (indoor) statistics of a senior in the month of Mar 2018.

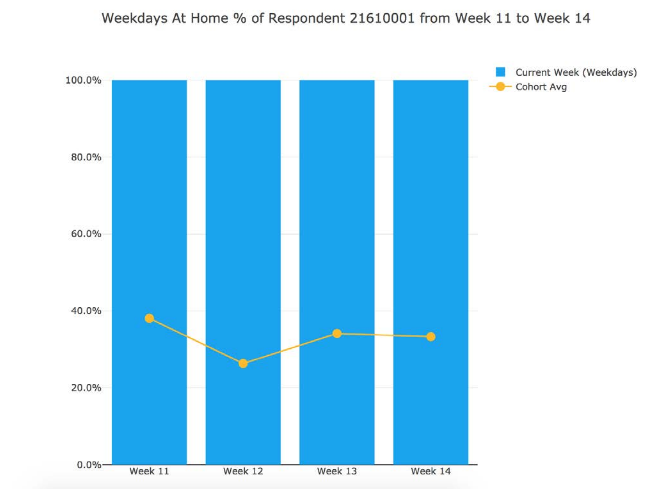

Fig. 6. Weekly at-home percentage of a senior as compared to the cohort average.

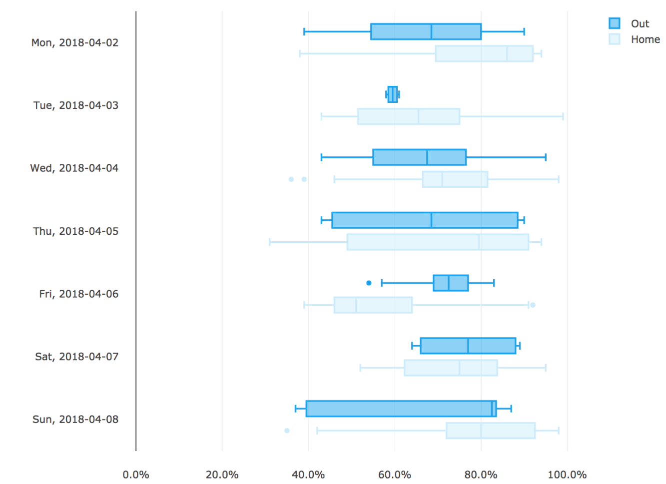

Fig. 7. Battery percentage of a senior's smartphone when he/she is outdoors vs at home.

A. At-Home (Indoor) Statistics

The aggregated and individual at-home (indoor) information of community dwelling seniors are extremely useful to the community caregivers, who are often looking for ways to maximize their care productivity, while not comprising on the quality of care.

Figure 4 illustrates the aggregate view of each participant's at-home (indoor) statistics, for different day of the week. The at-home statistics are computed based on the (historical) probability that the participant is at home, between the time periods of 7 A.M. and 10 P.M., which are the typical waking hours of a person. Such aggregate at-home statistics can be useful when planning and scheduling for activities at the senior activity centers (SACs), which are usually located within the community.

The detailed breakdown of the probability that the senior is at home, at a particular hour on a particular day, is illustrated in Figure 5. Based on the computed probability, caregivers are able to plan for individual home visits more efficiently, as they have a better understanding of the the senior's indoor/outdoor patterns at varying time intervals, and across different days of the week. In addition, the data allows caregivers to be able to detect changes in the senior's activity levels across different days of the week.

B. At-Home (Indoor) Trends

Figure 6 illustrates the senior's weekly at-home percentage, as compared to the cohort average. There are two key insights that can be drawn from this analysis.

Firstly, the senior's weekly at-home percentage over time (weeks) allows caregivers to identify seniors who exhibit changes (or anomalies) in their activity levels. Early detection of anomalies can help to prevent dangerous situations and enhance the quality of senior's lives [7], as well as allow caregivers to pay more attention to the senior.

Secondly, the comparison with the cohort average allows caregivers to have a better understanding of each senior's profile, and to identify seniors who are generally more at risk of social isolation and/or frailty, as compared to the rest of the seniors. The caregivers can then provide more targeted care and attention to these seniors, and encourage them to be more active by participating in community activities with their friends. Without such information, caregivers may be unaware of which seniors might actually require more care and assistance.

C. Battery Drain Patterns

The remaining battery percentage of the smartphone of a particular senior, with varying activity states (indoor/outdoor) is illustrated in Figure 7. Generally, it can be observed that the remaining battery percentage of the smartphone when the senior is outdoors, is lower than when he/she is at home. This is an ongoing research study of interest, whereby we can potentially use only the battery information of the senior, to determine if he/she is at home or outdoors.

V. Discussion and Future Work

With the ageing population in Singapore and worldwide, it is increasingly important to leverage technology to provide better care for, and to enhance the wellbeing of seniors who are living within the community. Previously, much effort has been placed on instrumenting homes with multi-modal sensors to improve physical safety (for instance, when the senior falls down), and/or to detect changes in behavioral patterns for early detection of particular illnesses. However, these 'smart homes' for seniors are often prohibitive in cost, and cater to older seniors who do not have smartphones.

The digital literacy and smartphone penetration rates of younger seniors (such as those who are currently in their 50s) are definitely much higher as compared their older counterparts. As such, alternative technological solutions can be harnessed to provide better care for the seniors. In this paper, we have proposed a low-cost and scalable method of quantifying the activity levels of seniors, through the use of Bluetooth beacons and the seniors' smartphones.

We have deployed our solution in the residential homes of 81 young seniors, over a period of 3 weeks. We have shown that the activity levels of each senior can be derived, based simply on the indoor and outdoor patterns of the senior. The derived activity patterns provide caregivers with a better understanding of the senior's travel patterns, allow anomalies to be detected over time, and allow community caregivers to provide more targeted care to the seniors whom they serve.

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