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Elderly Medication Adherence Monitoring with the Internet of Things

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Abstract—With the growth in elderly population in Singapore, healthcare expenditure and prevalence of age-related illnesses are expected to increase. Non-adherence among the elderly is a common issue that leads to adverse health complications, particularly among those with chronic conditions. However, existing studies typically focus on identifying predictors of medication adherence, and provide neither user-friendly nor actionable solutions that can be easily adopted by the elderly.

In this paper, we use the Internet of Things to monitor medication adherence and detect changes in medication consumption patterns among the elderly, thus enabling timely interventions by caregivers to take place. Sensor-enabled medication boxes are deployed in the residences of ten elderly participants for more than four months, since Jul 2015. Preliminary results indicate that our solution can effectively monitor medication intake patterns, and identify elderly who are non medication-adhering.

I. INTRODUCTION

Between now and 2030, Singapore will face the looming challenge of unprecedented profound age shift. According to the Committee on Ageing Issues in Singapore [1], the proportion of elderly will increase from 8.4% in 2005 to 18.7% in 2030. The ability to age with independence is important to the elderly, and this is closely associated with health issues - specifically, the prevalence of age-related chronic illnesses.

The lack of medication adherence is a pertinent problem that contributes to health issues of elderly, as they are generally more vulnerable to adverse complications that arise due to non-adherence. There is evidence to suggest that non-adherence has a significant negative impact on the effectiveness of treatment, leading to increased healthcare expenditure, morbidity and mortality in elderly [2].

Past literature has largely focused on identifying the predictors of medication adherence in elderly. The research approach to identify these variables [3] are often qualitative in nature. Focus groups and face-to-face interviews are the main medium of data collection. Such descriptive qualitative research designs are labor-intensive and may not yield high-accuracy data collection [2][3], as self-reported adherence is highly dependent on the individual's willingness to divulge information. In addition, such information on medication adherence is collected only periodically, which does not allow caregivers to respond timely to the elderly's non-adherence.

In this paper, we propose the use of Internet-of-Things (IoT) as a cost-effective method to: (i) monitor medication adherence in the elderly, thus allowing for subsequent personalized

intervention by their caregivers; and (ii) detect anomalies or changes in the elderly's medication consumption over time.

In this pilot study, our instantiation of IoT is a prototype sensor-enabled medication box and a gateway that is placed in each of the elderly residences. Each box is equipped with a reed switch and a low-power IEEE 802.15.4 radio. When the box is opened, the sensor node in the box is triggered to transmit messages to the gateway, which forwards the messages to the backend server. This data is then used to *infer* the medication adherence of the elderly, so that appropriate intervention by caregivers can take place.

Although there are existing sensor-enabled medication boxes in the market, these are typically of high cost and not widely adopted by the elderly. Through initial engagements with the elderly in our study, we have found that they are more receptive towards adoption of technology-enabled medication boxes, only if the box can be customized to their needs (e.g. size) and preferences (e.g. color), without adversely changing their current medication habits. Our approach allows the elderly to select off-the-shelf boxes according to their needs and preferences. These boxes are subsequently retrofitted with sensors for monitoring purposes.

The ten participants are selected based on the following criterion: above 65 years of age, has chronic illnesses, has to take medication everyday, and is willing to participate in the study. The medication boxes are placed in the elderly residences for more than four months since Jul 2015. In this paper, we present the results of the medication adherence pilot study through the use of IoT-enabled medication boxes, and highlight the efficacy of the box in monitoring medication adherence, as well as detecting anomalies or changes in the elderly's medication consumption.

The rest of this paper is organized as follows: Section II discusses background and related work in the literature. Section III describes the system design of the medication box that is used for *inferred* medication adherence, as well as the care model for the elderly. Performance evaluation results are presented in Section IV. We conclude the work with some directions for future work in Section V.

II. BACKGROUND AND RELATED WORK

Existing work focuses on the study of factors that influence medication adherence - such as gender differences, education level, health literacy, number of medication types, daily

pill counts, duration after diagnosis, depression and socio-economic status [3][4][5]. Most of these research studies use focus groups and interviews for data collection [6], which is extremely labor-intensive and requires trained personnel. Subsequently, only a small population sample size can be studied, and data accuracy is largely dependent on the willingness of the elderly to divulge information. These qualitative methodologies are unsustainable in providing scalable, efficient and timely long-term monitoring of medication adherence patterns.

Past research that tests the effectiveness of interventions to improve medication adherence have inconsistent results [7] and do not yield significant improvements in adherence rates [8]. [9] suggests that targeted and personalized interventions between patients and pharmacists can improve medication adherence. [10] reveals that interventions applying special medication packaging, participant monitoring of medication effects and side effects, succinct written instructions and dose modification are more effective. Unfortunately, these methods require more direct feedback in the monitoring process, and do not take into account elderly who are illiterate.

There are commercial products that are targeted at improving medication adherence. MedMinder [11] utilizes visual and/or auditory alerts to remind users to take their medication. AdhereTech [12] issues personalized alerts and interventions whenever the elderly misses their dosage. Medipac [13] uses optical sensors and Bluetooth to transmit information from the pill box to the mobile application, and the elderly receives timely reminders via text messages or voicemail. However, these products are often expensive with recurring costs, and inflexible as they cannot be customized according to the elderly's preferences and medication intake requirements.

This paper proposes a cost-effective solution that enables caregivers to monitor the medication consumption trends of each elderly, and to detect anomalies in their behaviors. We consider factors such as the complexity of individual medication regimes, ease of use of the medication box, battery lifespan of the sensor device, broadband availability in the elderly's home and literacy level of the elderly. We use off-the-shelf boxes with flexible compartments, which can be customized to each individual elderly's prescription and preference. Our solution is also extensible to include scalable and personalized passive intervention - such as buzzers - when the elderly misses his/her medication.

III. SYSTEM DESIGN AND CARE MODEL

A. Sensor Node

Each medication box may have multiple (between one to three) compartments. Each compartment is retrofitted with a uniquely identifiable sensor node, comprising:

- an Arduino-based microcontroller board;
- a normally closed (NC) reed switch that is connected to the microcontroller; and
- a low-power IEEE 802.15.4 radio for transmissions.

The NC reed switch and magnet are placed at strategic locations inside the medication box, such that the reed switch

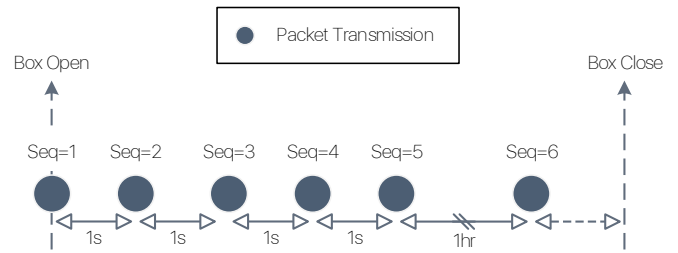


Fig. 1. Packet transmission schedule of sensor node.

and the magnetic field are in contact whenever the box is closed (either through the lid or drawer). In this state, the internal contacts of the (normally closed) reed switch become open due to the influence of the magnetic field, and effectively stops the electrical current from flowing through. Hence, the entire sensor node is powered off and battery consumption is minimized during most parts of the day - when the medication box is closed.

When the elderly opens the lid or drawer of the medication box to take his/her medication, the NC reed switch breaks contact with the magnetic field. This causes the NC reed switch to operate in its normally closed state, whereby electric current can flow through, thus allowing the node to be powered up. The node will then send periodic packets (with increasing sequence numbers) to the nearby gateway(s) through the IEEE 802.15.4 radio, for the duration of time that the medication box is in a physically opened state.

The sequence numbers of the packets restart from one when the sensor node is powered off upon the physical closure of the medication box; this allows the differentiation between packets triggered by: (i) opening of the box; and (ii) prolonged non-closure of the box. The latter scenario prevents the detection of subsequent medication intake by the elderly; hence, the caregiver will typically remind the elderly (through a telephone call) to close the medication box when the system detects such a scenario. Figure 1 illustrates the packet transmission schedule of the sensor node when the box is first opened, and left opened for an hour, before being closed again.

B. Gateway Node

The gateway node is a Beaglebone Black (BBB) device that is equipped with:

- an IEEE 802.15.4 radio for transmissions between the sensor node and itself; and
- a 3G dongle for backhaul communications to the backend server.

Upon receiving packets from the sensor node(s), the gateway will publish data to the backend server, through the use of MQTT [14] - a publish/subscribe messaging protocol designed for lightweight communications. The gateway also provides auxiliary services, such as time synchronization through the Network Time Protocol (NTP).

C. System Architecture

The simplified system architecture is shown in Figure 2. An anycast routing mechanism is used for communication

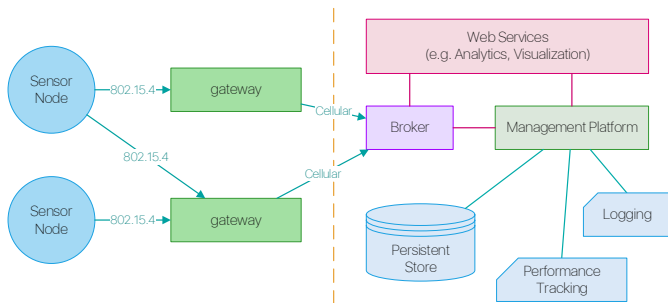


Fig. 2. Simplified system architecture.

between sensors and gateways, such that a sensor node can transmit packets to *any* gateway within its vicinity. This has the dual benefits of:

- reducing the number of gateways required in the system, which can lead to significant cost savings if the density of elderly residents who are using the system is high; and
- increasing the robustness and reliability of the system through elimination of single points of failure.

In highly urbanized cities such as Singapore, the use of anycast is of particular importance due to the high population density - whereby many residents live in close proximity to one another. Elderly residents who are staying near each other can rely on the same gateway for sensor data to be forwarded towards the backend. In our study, the elderly residents belong to the lower income group and have no individual broadband access at home. The use of anycast helps to reduce the overall cost of the system through reduction in the number of gateways required to support the entire system.

Upon receiving packets from the gateway(s), the backend server will then perform the necessary data cleaning (such as removing duplicates, if any), data analysis, data visualization and other network management functions.

D. Elderly Care Model

Sensor-enabled medication boxes allow for timely and long-term monitoring of the elderly's medication consumption patterns. Through analysis of both sensor data and survey data on the elderly's lifestyle and medication-related information (such as medication types and replenishment patterns), each elderly can be classified into one of two categories: (i) medication adhering; and (ii) medication non-adhering.

Elderly who are medication adhering will be monitored continuously for any changes in consumption patterns over time. Elderly who are medication non-adhering and have given prior consent, will be provided with intervention measures such as: (i) medication reconciliation by medically-trained professionals; and (ii) medication reminders by caregivers. Figure 3 summarizes the holistic care model (involving both technology and caregivers) for elderly medication adherence.

IV. EVALUATION AND DISCUSSION

A. Participant Recruitment and Deployment

A total of ten elderly participants are recruited for the medication pilot study, from a larger pool of fifty elderly residents

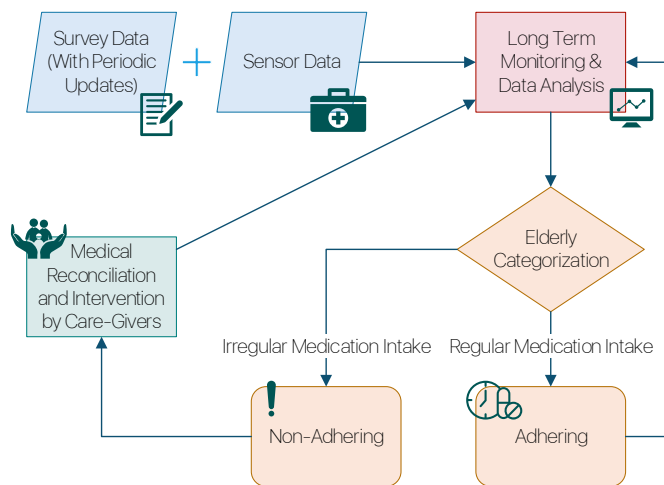


Fig. 3. Care model.

whose residences have been instrumented with PIR (passive infra-red) sensors for activity monitoring. A set of medication box and gateway is deployed in the residence of each of the ten participants for a period of more than four months, since Jul 2015. Prior to the commencement of the deployment, a survey is administered to each elderly, to gather data on their demographics, physical health (such as number and types of chronic illnesses) and medication consumption habits (such as daily medication intake frequency, types of medication and receptiveness towards technology-enabled medication boxes).

The ages of the elderly range between 69 to 81 years old, and each of them is diagnosed with three to eight chronic illnesses - such as diabetes, hypertension and high blood pressure. Each elderly consumes four to ten types of medication, and daily medication intake frequency ranges between one to three. Due to space constraints, we highlight results from only three selected elderly participants in the study.

B. Inferred Medication Intake Frequency

Figure 4 illustrates the inferred daily medication intake frequency of three elderly participants, whom we refer to by their identifiers, namely 1090, 1070 and 1060. Periods of system maintenance are indicated; these are typically due to hardware-related issues - such as accidental switching off of the mains-powered gateway by the elderly, battery drain of the sensor node (due to prolonged non-closure of the medication box) and SD card corruption in the gateway. The corresponding monthly intake statistics of the three elderly are shown in Figure 5.

Elderly 1090 has a consistent statistical mean value of 2 for the daily medication intake frequency across the months from Jul to Oct 2015, which corresponds to the intake frequency as indicated in her survey results. Her medication intake appears to be very regular; hence, she does not require any form of intervention by her caregivers.

Elderly 1070 was hospitalized between 15 Jul to 17 Jul, and 2 Aug to 25 Aug 2015. This accounts for periods of lapses in his daily medication intake, as well as the increased variation

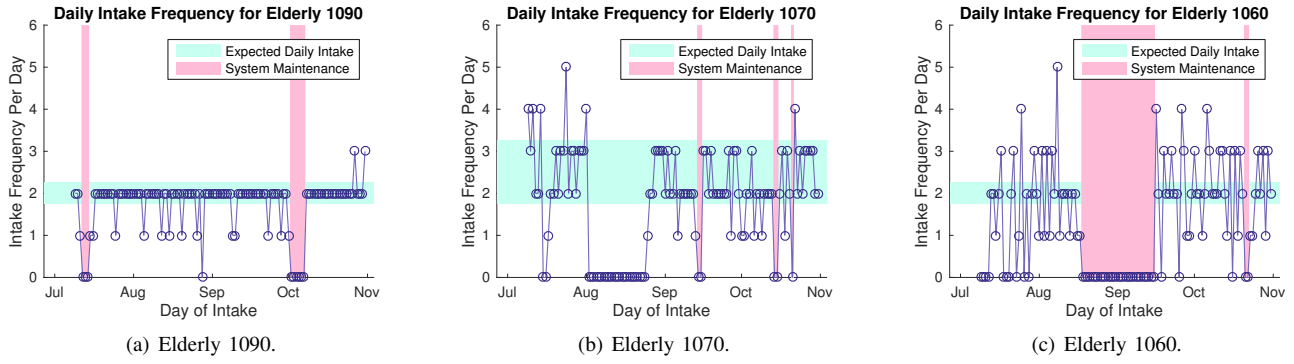


Fig. 4. Daily Medication Intake Frequency.

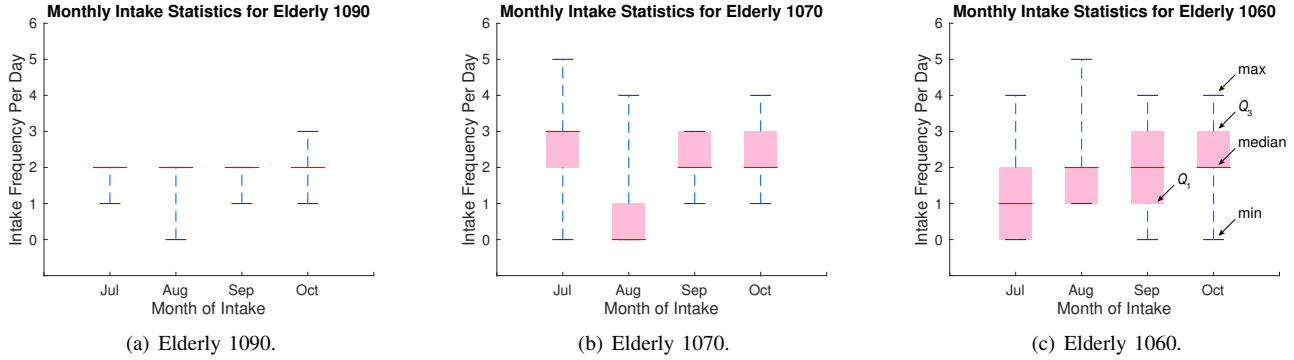


Fig. 5. Monthly Medication Intake Statistics.

in his monthly medication intake statistics as compared to Elderly 1090. In retrospect, it appears that his medication intake consumption had increased just before he was hospitalized. The elderly had also communicated to his caregiver that he was feeling unwell between 21 Oct to 23 Oct, which may account for his increased medication intake (beyond the value of 2 to 3 as indicated in his survey) on 22 Oct 2015.

Upon corroboration with the PIR activity monitoring system that is installed in the elderly’s residence, it is also found that Elderly 1070 occasionally misses medication dosages due to prolonged periods (of more than 10 hrs) of being away from home for the day. This typically happens on Sundays, during which the elderly tends to engage in outdoor activities.

The daily medication intake frequency of Elderly 1060 appears to indicate that he does not have a regular medication regime. His medication intake frequency has a high variation from the indicated value of 2 in his survey. Through his caregiver, it was discovered that Elderly 1060 often opens his medication box to pack and/or replenish medication.

C. Medication Intake Timings

To study the regularity of the timings during which the elderly consumes his/her medication, we use Density-Based Spatial Clustering of Applications with Noise (DBSCAN) [15] to cluster the medication intake timings. The following DBSCAN parameters are used in our evaluation:

- 1) distance function, which we define to be the cyclic difference between any two medication intake timings;

- 2) $\epsilon = 1$ hr, which is the maximum distance between two medication intake timings that can be considered to belong to the same cluster; and
- 3) $MinPts = 5$, which is the minimum number of points in the cluster (ϵ neighborhood).

DBSCAN is preferred over other clustering methods (such as k -means-clustering), as it: (i) does not require the number of clusters to be known *a priori*; (ii) is robust to outliers; and (iii) does not assume that clusters are of the same size.

Figures 6 and 8(a) illustrate the distribution of medication intake timings of Elderly 1090, for the months of Aug to Oct 2015. The intake timings can be consistently grouped into two distinct clusters throughout the months: (i) 8 A.M. to 10 A.M.; and (ii) 6 P.M. to 8 P.M., which corroborates with her expected intake frequency of twice per day.

The distribution of the medication intake timings of Elderly 1070 from Aug to Oct 2015 are shown in Figure 8(b). As the elderly was hospitalized for a long period of 24 days in the month of Aug 2015, there are insufficient data points to form meaningful clusters using DBSCAN. For the remaining months from Sep to Oct 2015, his medication intake timings can be grouped into three distinct clusters: (i) 7 A.M. to 9 A.M.; (ii) 12 P.M. to 1 P.M.; and (iii) 5 P.M. to 7 P.M., which is consistent with his expected intake frequency of twice to thrice per day.

Finally, we study the medication intake timings of Elderly 1060 in Figures 7 and 8(c), which has a somewhat consistent cluster between 8 P.M. and 12 A.M. (night dosage), but

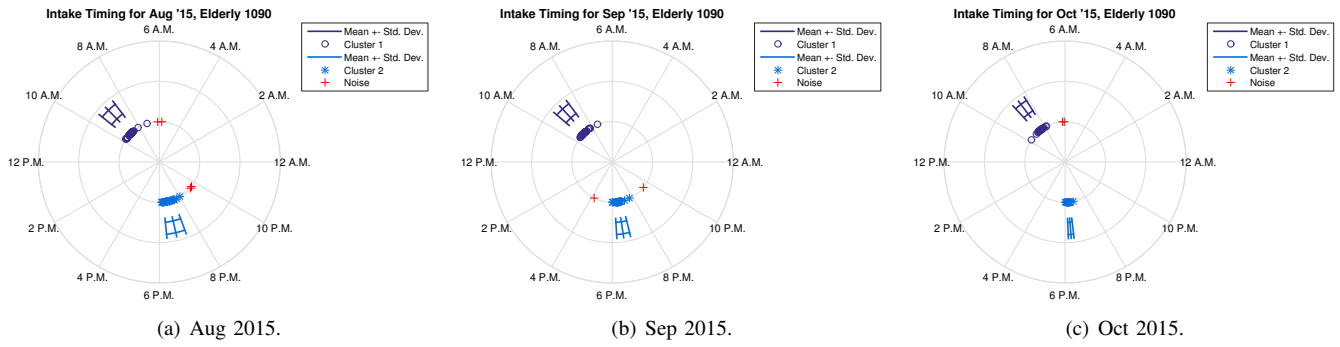


Fig. 6. Medication Intake Timings for Elderly 1090.

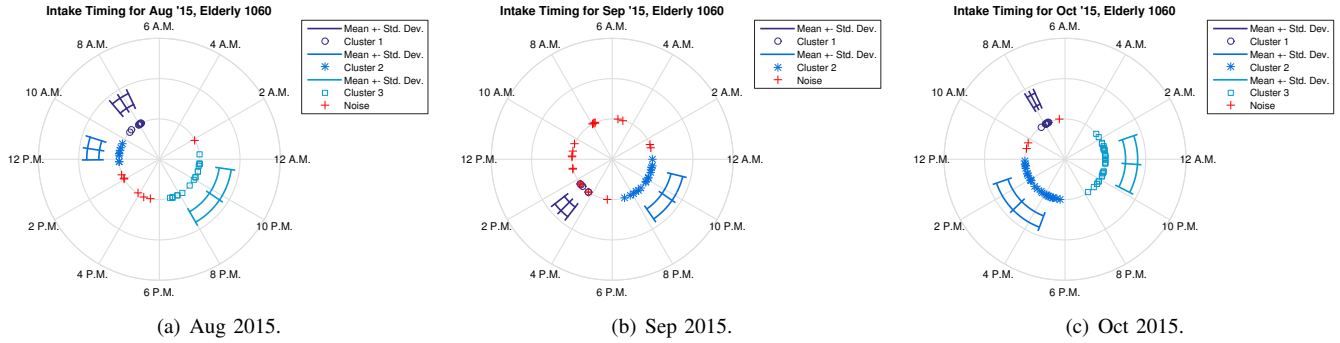


Fig. 7. Medication Intake Timings for Elderly 1060.

generally inconsistent intake timings throughout the rest of the day. This may be due to his lack of a regular lifestyle, as observed by the PIR activity monitoring system in his residence, as well as through conversations with his caregiver.

D. Ground Truth Evaluation

We evaluate the accuracy of the sensors in detecting the usage of the medication box, through which medication intake is inferred. Five of the ten elderly were selected to keep a medication diary for two non-consecutive weeks (based on their cognitive ability and willingness to participate). Each elderly was compensated with USD14 accordingly, for their time and effort in completing the medication diaries.

Figure 9 compares the diary records with the sensor readings for Elderly 1090 and Elderly 1070. Generally, the sensor-enabled medication box used by Elderly 1090 is able to capture the diary records, with an accuracy of 96%. In the case of Elderly 1070, the accuracy of the sensor-enabled medication box was much lower at 67% after the first week of diary recordings. A firmware update was subsequently applied to all the sensors in the study, to reduce the missed detections by reducing the delay incurred in transmitting the messages to the gateway when the medication box is opened. After the firmware update, the sensor-enabled medication box was able to achieve 90% accuracy during the second week of the diary recording by Elderly 1070.

In general, discrepancies between actual medication intake and sensor recordings of medication intake are likely to arise due to: (i) sensor placement in various medication box configurations; and (ii) non-closure by the elderly after use,

thus reducing the level of accuracy. The latter scenario is alleviated through the detection of periods when the elderly does not close his/her box, and giving the elderly a call to remind him/her to close the box as soon as possible.

E. Discussions and Insights

In the course of our pilot study, we derive several important insights that influence the effectiveness of using IoT to monitor elderly medication adherence. Firstly, many elderly have concerns about the electrical consumption of the mains-powered gateway, and attempt to save electrical costs by switching the gateways off. This challenge is overcome by explaining the system design to the elderly, and reassuring them that the gateways consume minimal electricity (USD 40 cents per month). Secondly, some of the elderly have very active lifestyles, which upsets their daily medication routine. A proportion of these elderly bring their medication out with them in a smaller (un-monitored) container, and the remaining miss their medication when they are out. Thirdly, our solution can only infer medication consumption, and cannot determine if the elderly has consumed the right dosage and type of medication. We are currently working with medically-trained caregivers to refine the design and use-case of the medication box, to allow for finer-grained monitoring and ground-truth evaluation of medication consumption. Other challenges in the study include: (i) the drainage of batteries when the elderly forgets to close his/her medication boxes; and (ii) frequent packing and unpacking of medication by the elderly, which affects the frequency that they access the medication box, through which medication intake is inferred.

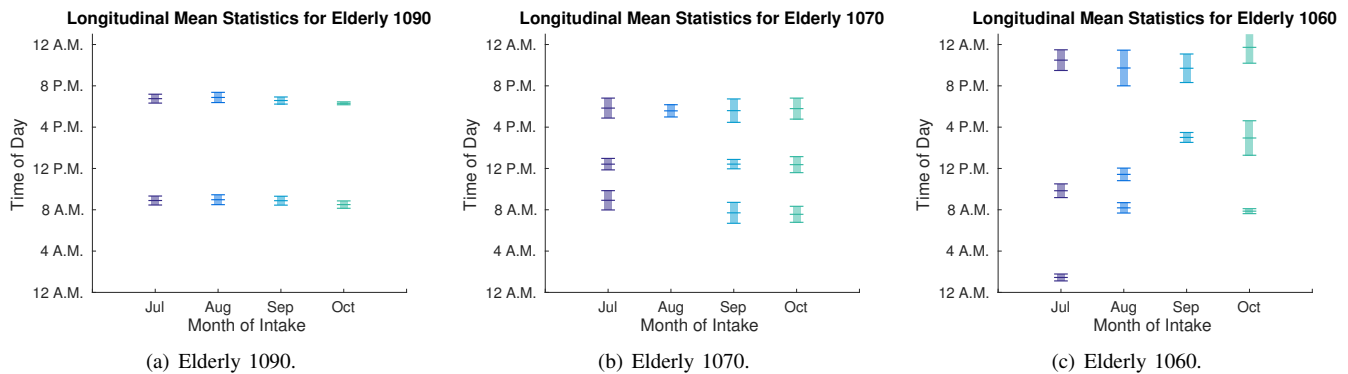


Fig. 8. Longitudinal Mean Statistics of Medication Intake Timings.

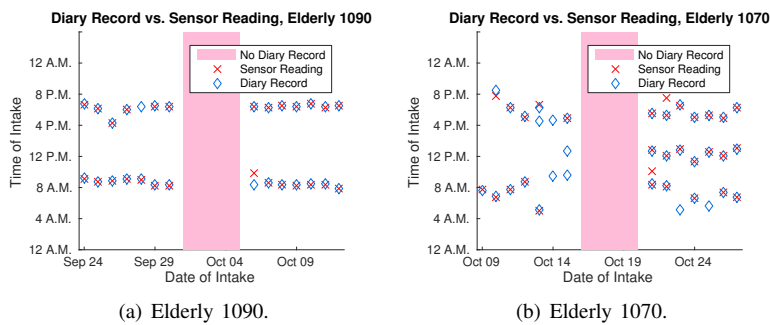


Fig. 9. Diary Record vs Sensor Reading.



(a) Single-compartment. (b) Three-compartments.

Fig. 10. Medication box configurations.

V. CONCLUSION AND FUTURE WORK

Our pilot study is effective in providing a solution to monitor medication adherence, and detect changes in the elderly's medication consumption patterns. With the low-cost and customizable solution, we have been successful in convincing elderly participants to adopt the use of sensor-enabled medication boxes. The analyzed sensor data empowers caregivers with the information to intervene before the elderly's health deteriorates. With the adoption of our unobtrusive solution, the effectiveness of medical treatment can be increased and wastage of healthcare resources can be reduced.

As part of future work, we intend to increase the duration and scale of the study to more elderly participants to derive both longitudinal and transversal insights in medication adherence. We also intend to work more closely with caregivers and medical professionals to better provide a holistic care model for improving medication adherence in elderly.

ACKNOWLEDGMENT

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