An Interoperable Pillbox System for Smart Medication Adherence

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***Abstract*— We have designed and fabricated an interoperable system for medication adherence. The system is composed of a pillbox that wirelessly communicates with a computer application and a custom-made wristband. The system receives the information of taking specific medication from the user or caregiver, reminds the user to take the medication, monitors the user's hand gesture during the medication intake and monitors the compartments of the pillbox for refilling purpose. The performance of the developed system was examined in various bench-top scenarios. The system has the potential to improve the existing systems by reminding the user to take the medication through the wristband, automatically collecting user's hand gestures during the medication intake, and providing detailed information about the existence of medication in the compartments of the pillbox.**

I. Introduction

In 2010, there were more than 40 million Americans 65 years or older. Increased age increases the probability of suffering from multiple medical and chronic conditions such as hypertension [1, 2], heart failure [3, 4] and high cholesterol [5], resulting in increased use of prescribed and over-the-counter medications. According to the Centers for Disease Control and Prevention, more than 76% of Americans aged over 60 used more than 2 prescription drugs and 37% used five or more. Farrell et al., found that older adults (average age 81 years) take an average of 15 medications daily [6].

Most of the current methods for assessing adherence to medication regimens only verify the most recent usage of the medication and do not provide any information about compliance between clinical visits [7]. Therefore, these methods suffer from "white-coat compliance", where the patient may be noncompliant until shortly before a clinic appointment and return to noncompliant behavior after the clinical visit [8]. Self-reporting methods such as patient-kept diaries and pill counts are found to overestimate patients' adherence [9] and will not function for people with diminished memory. Interview- and questionnaire-based methods are not reliable because they depend on how the questions are designed and asked [10].

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Various electronic pillboxes have been developed in both industry and academia during the past three decades and in the recent years. However, each system can only accommodate limited aspects of medication adherence. For instance, widely used Medication Event Monitoring System [11] (MEMS, Aardex Ltd.) does not report adherence in real time, so intervention cannot take place if medications are missed. The reminder alarms of the "E-pill Medication Reminder" products only cover a limited audible range. If the user leaves the accessible range (e.g., indoor environment), s/he may miss the dosage [12]. Hayes et al. [13], developed a standalone electronic pillbox that benefits from the modification of a readily-available 7-day reminder pillbox. However, the system is preliminary and does not provide some of the aspects of the adherence such as a reminder to refill the pillbox or an audio (or visual) reminder. The system by Abbey et al. also does not provide the refill option [14].

We have developed an interoperable system that is composed of three subsystems; a pillbox, a computer and a wristband. All the subsystems are wirelessly communicating with each other. Whenever it is the time to take the medication, the computer transmits a reminder signal to the wristband to notify the user to take the medication. The computer also sends a signal to the pillbox. When the user gets to the proximity of the pillbox, the radio frequency identification (RFID) reader on the pillbox detects the embedded RFID tag on the wristband and rotates the lid of the pillbox to provide access for the user to the appropriate compartment. When the user takes the pill, a pair of diode and photodiode embedded in each compartment detects the empty space in the compartment and the lid closes. The pillbox updates the status of the compartments and sends a wireless signal to the computer to remind the user or caregiver to refill the pillbox. The system was successfully tested in three different scenarios on bench-top setting. The procedure to develop the system, the system flowchart and the result of testing the system is provided in the following sections.

II. System Overview

The medication adherence system is composed of three subsystems; a pillbox a wristband, and a computer. Fig. 1 shows these subsystems and the wireless communication between them.

A. Pillbox

A pillbox with 7 compartments was designed in AutoCAD (Autodesk, Inc.) and fabricated with a 3-D printer (MakerBot Replicator 2, MakerBot Industries). The pillbox is in cylindrical shape (∅ 126 mm × 56 mm) and is composed of three pieces; a top lid, a middle piece that contains the

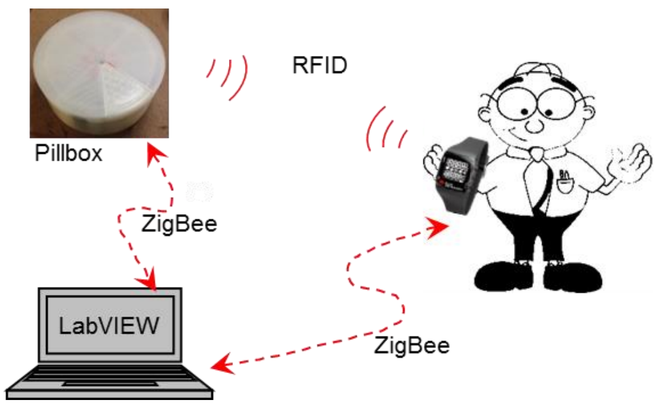

Fig. 1. The block diagram of the medication adherence system is shown. The system is composed of a custom-made pillbox, a wristband with motion and temperature sensors, and a computer that are wirelessly connected to each other.

compartments, and a bottom piece that encases a stepper motor (Mercury Motor SM-42BYG011-25), an RFID reader (13.56 MHz), and a ZigBee transceiver (XBee with 1mW Trace Antenna, Series 1, IEEE 802.15.4 standard) that are all managed by a microcontroller board (Arduino Fio, ATMega328P). Fig. 2 shows the fabricated pillbox, integrated with the electronic components. Each compartment has a photodiode and a diode, on the inside edge of the perimeter and on the edge close to the stepper motor's vertical axis, respectively. The diodes emit light and depending on the blockage caused by the solid-phase medication, i.e. pill, the photodiode generates different voltage levels. When it is the time to take the pill, and the RFID reader in the pillbox, detects the RFID tag (embedded in the wristband) in the vicinity, the stepper motor rotates the lid to the make the predetermined pill available to the user. If the RFID reader does not detect the tag, it will send a message (through ZigBee) to the computer to

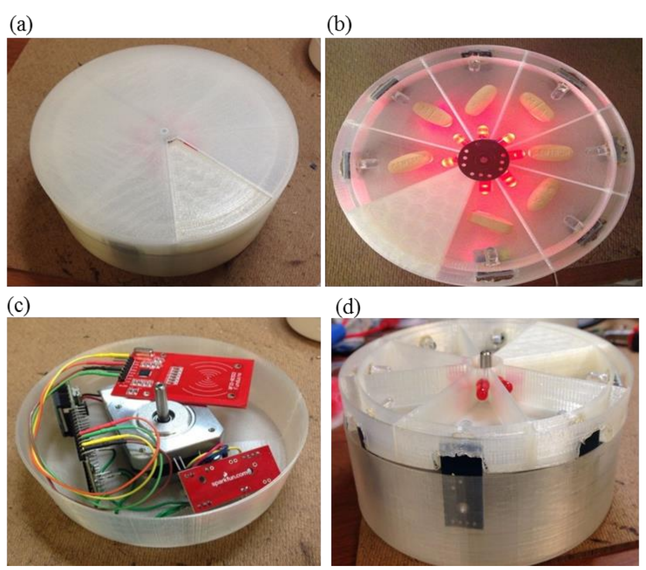

Fig. 2. The different pieces of the pillbox are shown. (a), (b), and (c) are showing the lid piece, the middle piece that encompasses the photodiodes and diodes, and the bottom piece that includes the RFID reader, the stepper motor, the XBee and the microcontroller board, respectively. (d) Shows the middle and the bottom pieces integrated from the side view.

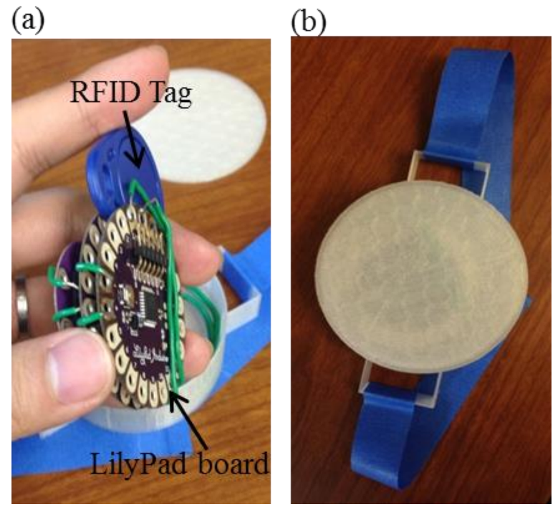

Fig. 3. Shows the fabricated wristband. (a) Shows the microcontroller board (LillyPad) on the top, the RFID tag. The XBee transceiver and the battery management boards are located in the middle and bottom, respectively. The motion sensor is located on the back of the Lilypad board and the temperature sensor hidden on the back side of the battery management board. (b) Shows the electronics encased in the wristband.

remind the user.

B. Wristband

The wristband is developed upon Arduino LilyPad board that includes an ATMega328 microcontroller. A MPU-9150 chip (by Invensense), which integrates a tri-axis accelerometer (programmable full scale range of ±2g, ±4g, ±8g and ±16g), a tri-axis gyroscope (sensitivity of up to 131 LSBs/dps and a full-scale range of ±250, ±500, ±1000, and ±2000dps), and a

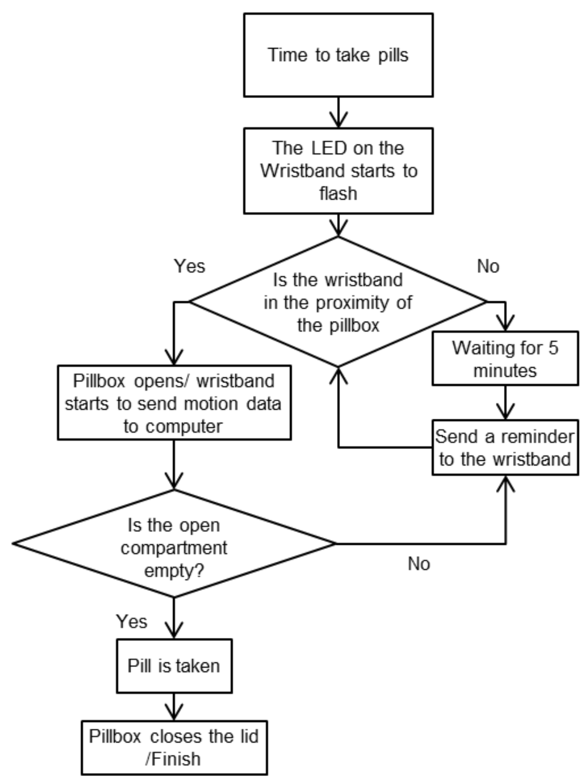

Fig. 4. The flowchart of the system is shown.

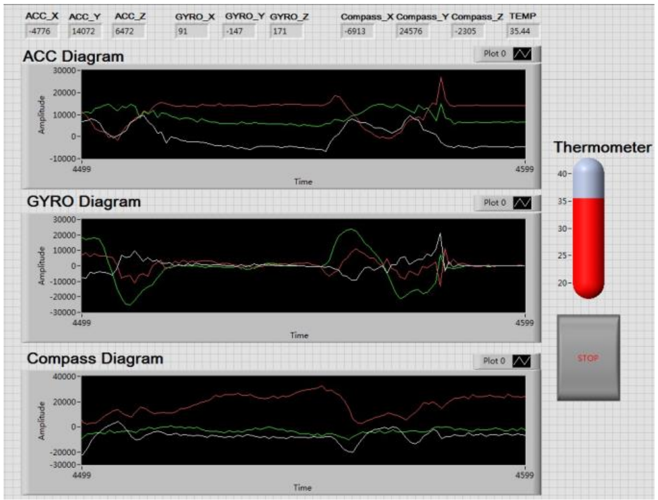

Fig. 5. The front panel of the custom-made program developed in LabVIEW is shown. This program is used for data acquisition from the sensors. The tri-axis data from accelerometer, gyroscope and compass sensors are plotted in real-time in different colors (x in white, y in red, z in green).

tri-axis compass (full scale range of ±1200μT), communicates with the microcontroller through Inter-Integrated Circuit (I^2C) bus. A temperature sensor is also embedded in the wristband that can measure from −25 °C to +85 °C with 0.0625 °C sensitivity. The wristband is also equipped with a ZigBee transceiver (similar to the pillbox), an LED, and an RFID tag (13.56 MHz). The wristband reminds the user to take the medication by flashing the LED. When the wristband reaches to the proximity of the pillbox, it starts to record from all sensors at the sampling rate of 20 Hz (per axis per sensor), and wirelessly transmits the signals to the computer. Figs. 3 and 4 show the fabricated wristband and the flowchart of the system, respectively. The encasing was designed in AutoCAD and implemented with the 3-D printer.

C. *Computer*

Two computer applications have been developed. One application receives the information about the type and the instruction of each medication from the user or caregiver. In this paper, we discuss the second application that is exclusively developed for data acquisition from the motion and temperature sensors. This application, which is developed in the LabVIEW (National Instrument), wirelessly receives the signals from the wristband, plot the signals in real-time and restores them for off-line analysis. A ZigBee receiver that is connected to the computer receives the information from the wristband and sends them to the computer through a serial communication (57600 Baud rate). The Computer also communicates (ZigBee) with the pillbox and receives the updated information regarding the status (filled or empty) of the pillbox's compartments. Fig. 5 shows the front panel of the developed LabVIEW program. The data recorded from the accelerometer, gyroscope and compass sensors are plotted in real-time in different colors (x in white, y in red, z in green). Also the temperature information is plotted in real-time in a vertical thermometer gauge.

III. System Validation

The medication adherence system was examined in three different scenarios. The functionality of the system during each scenario is described below:

A. *Scenario 1: The Subject Complied and Took the Medication with the First Reminder*

In this scenario the LED on the wristband started to flash to remind the subject to take the medication, while the subject was approximately 5 m away from the pillbox. The subject complied with the reminder and approached to the pillbox. The subject swiped the wrist against the pillbox. The maximum sensing distance between the wristband and the pillbox was measured at 4 cm. The wristband started to transmit the motion signals to the computer. The stepper motor in the pillbox rotated the lid and the subject took the pill (a multivitamin) and walked away. The signals received from the wristband were restored and plotted in MATLAB (MathWorks) in off-line (Fig. 6). During this experiment, the wristband was worn on the subject's right hand (dominant hand), and the subject took the pill with the same hand. The lid of the pillbox was closed automatically and the status of the pillbox's compartments in the computer was updated through the signal sent by the pillbox. This experiment was repeated 5

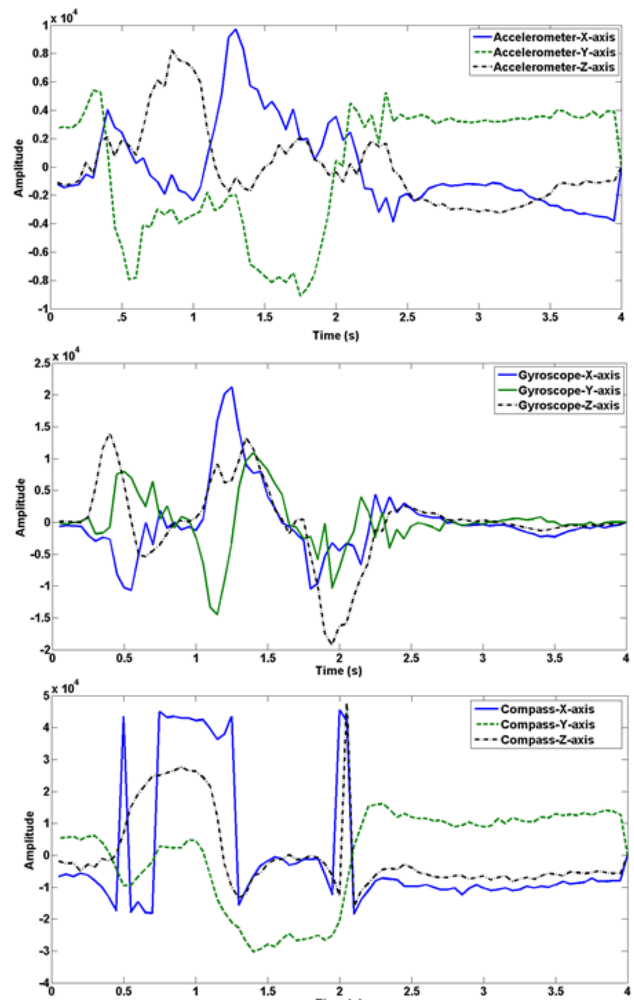

Fig. 6. The motion sensors data received from the right hand of the subject during the medication intake action are plotted.

times and the layover of the recorded signals showed that the pattern is relatively consistent.

B. Scenario 2: The Subject did not Comply with the First Reminder

In this scenario the wristband reminded the subject to take the medication; however, the subject did not comply. The LED on the wristband flashed for one minute and turned off. The system waited for additional four minutes and started to flash the LED again. This time the subject approached the pillbox and took the pill. The rest of the scenario was followed similar to Scenario #1.

C. Scenario 3: The Status of the Pillbox was Updated in the Computer

In this scenario the ability of the photodiodes to detect the existence of the pills in the compartments was examined. The pills were placed in two extreme cases; perpendicular and parallel to the photodiodes. We used multivitamin pills that approximately measures 20mm × 7mm × 5mm. The system was examined for individual compartments, and for the combination of compartments, when: a) all the compartments were filled, b) half of the compartments were filled, and c) all the compartments were empty. The results showed that the system was able to accurately detect the existence of the pills in the compartments. The results also showed that the system can accurately measure the existence of the pill when the lid is open and it is exposed to the light coming from the outside environment. During this experiment the luminance of the environment was measured at 200 lux.

IV. Discussion and Conclusion

We have developed an interoperable system for medication adherence. The functionality of the system was demonstrated in three different scenarios. The pill taking experiment in the Scenario #1 was repeated 5 times and the layover of the recorded signals showed that the patterns are relatively consistent between the experiments. If this consistency can be proved, one can potentially use the developed system to detect the hand gestures related to taking medication. We will continue to collect more hand gestures data with the developed wristband and perform further analysis on the data to construct a comprehensive data set of hand gestures during the medication intake action.

Although the pillbox was designed to only have seven compartments (one pill per day), it can easily be modified to accommodate more pills. The design also needs to be optimized for smaller pills. We will perform this optimization using the results and guidelines obtained in the scenario #3. The results obtained from Scenarios #1-3 showed that the system can accurately perform according to the design specifications. However, more experiments are required to demonstrate the usability and acceptability of the system among the target users that are meant to be the geriatric population.

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