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Research paper

mPillBox: An open framework for a smarter pillbox

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ABSTRACT

As the medical and technological fields have improved, there is a growing reliance on technology in the medical field. A considerable issue plaguing patients around the world is the management of medication intake for medications that treat chronic or otherwise serious illnesses. As such, many hospitalizations or even deaths are caused by medication errors. Existing solutions that provide smart pillboxes make many assumptions regarding patients, such as patient due diligence regarding expiration dates, storage atmospheric conditions, medication interactions, and awareness of alerts. mPillBox is introduced and presented as an open framework for making a pillbox smarter. The purpose of mPillBox is to improve user medication adherence and ensure medications remain effective. mPillBox aims to revolutionize existing smart pillboxes by introducing several key features: By attaching itself, via a Raspberry Pi, to any pillbox, mPillBox allows a user to manage a schedule for their medications. Unlike other digital pillboxes, mPillBox allows users to check expiration dates and atmospheric conditions to ensure the efficacy of their medications. mPillBox provides an automated medication interactions checker that informs the user of any interactions for current or future medications. Furthermore, mPillBox relies on Internet of Things devices in the vicinity, such as Chromecast, to automatically alert users. This is managed by a newly proposed mPillBox algorithm. These key features provide the necessary means for ensuring proper medication intake and medication efficacy that are not available in existing smart pillboxes. mPillBox is a low-cost system, with no required subscription fees, that does not require any medical or technical professional to set up, allowing it to be deployed anywhere. An mPillBox prototype was implemented along with an iOS mobile application to allow any user or patient to turn their simple pillbox into a smarter pillbox for managing their medication intake. The results show that mPillBox is a low-cost and user-friendly system that is smarter and more effective than existing smart pillboxes.

1. Introduction

With technology and medical advances, healthcare has drastically improved around the world. The Internet of Things has brought about the improvement of patient care, hospital and pharmaceutical processes, and data accuracy (Lana Gates, 2021; Ben Forgan, 2021). Continuous blood glucose monitoring, automated insulin delivery, transferring vital patient data from the ambulance to the hospital, ingestible sensors for monitoring dosage intake, and wearables such as heart rate cuff monitors are a few examples of Internet of Things applications in the medical field. The advancement of medical and pharmaceutical research led to the creation of new medications that can manage chronic diseases. These medications can extend a patient's lifespan by decades but must be carefully monitored and rigorously taken.

Patients with chronic diseases and multiple medications generally rely on pillboxes to manage and schedule their medication intake (Schwartz, 2017). While these pillboxes improve medication adherence to a certain extent, they do not fully prevent medication errors and missed doses. Poor medication adherence can affect the quality and length of life and can account for up to half the treatment failures, billions of dollars in medical costs, and a large portion of medication-related hospital admissions in the United States alone (Tahir, 2015; Kim et al., 2018; Abbey et al., 2012a; Hayes et al., 2006). As such, research has been explored using various technologies and the Internet of Things to combat these issues (Lana Gates, 2021).

To assist in managing and scheduling medication intake, research in smart pillboxes has been explored (Tsai et al., 2011). Research developed and commercially available for smart pillboxes is focused on managing and scheduling medication. These smart pillboxes generally come prepackaged with a pillbox and are managed via a screen that provides information on medications. Additionally, some smart pillboxes offer a mobile application to set them up and provide alerts that are strictly sent through the pillbox or mobile application.

While available smart pillboxes provide reasonable methods for medication intake tracking, they make assumptions that might cause treatment failure: First, they assume medications are effective. Existing solutions for smart pillboxes generally do not address issues stemming

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from expired, possibly ineffective, medications. For example, a patient may be prescribed a life-saving medication that is used long-term. If the medication expires, while not necessarily harmful, the medication might lose its efficacy, rendering the treatment ineffective (U.S. Food & Drug Administration, 2021; National Health Service (NHS), 2020). This is especially concerning as some patients lose track of the expiration date of their medications once deposited in their pillboxes. Additionally, some environmental factors such as high temperature and humidity might render the medications ineffective (Funk et al., 2021; Deb Balzer, 2023). Second, existing solutions generally assume a single source of prescriptions, either a hospital or a pharmacy. This creates a single entity that holds all the prescriptions and records for the patient. For example, a patient may be prescribed a medication for a chronic disease while getting an over-the-counter medication or getting prescribed a different medication in another hospital. Medications might interact and decrease the efficacy of the medication, increase unexpected side effects, or lead to serious complications that may be fatal (Drugs.com, 2023a; Wang et al., 2009; Zao et al., 2010). These medication errors and side effects are among the most common causes of medical errors (U.S. Food & Drug Administration, 2023; National Coordinating Council for Medication Error Reporting and Prevention, 2023; Wang et al., 2009; Zao et al., 2010; Institute of Medicine, 2000). Third, they assume a patient is always near the device or their smartphone and so the alerts are usually confined to the device or mobile application through notifications.

To address these issues stemming from the assumptions and shortcomings of previous research and products, mPillBox is introduced. mPillBox provides a low-cost Internet of Things smart pillbox that manages and tracks medication intake, ensures medication efficacy, and provides information on medication interactions. First, mPillBox provides medication alerts to the user through the Internet of Things. Second, mPillBox ensures medication efficacy by checking the environment and conditions of the pillbox. Third, mPillBox provides alerts to the user on medication interactions. Additionally, mPillBox does not require nor rely on input or management from a hospital, pharmacy, or clinic. This decoupling from health services allows the user portability and more freedom for utilizing a single pillbox for all medications. In addition, it simplifies the process for the user by not requiring them to adhere to a system, hardware, or pillbox layout provided by a specific health entity. Note that mPillBox does not assume the role of a hospital, doctor, or pharmacist; It only provides guidance to the user. The ultimate course of action should be followed up with a qualified doctor or pharmacist.

The contribution of mPillBox is to provide a smart pillbox that minimizes errors due to missed medication doses or ineffective medications by adding measures that prevent these errors that are unavailable in existing solutions. Additionally, this paper reviews existing smart pillbox technologies. mPillBox contribution ensure any pillbox can be turned into a smart pillbox that (a) utilizes the Internet of Things, (b) incorporates a medication interactions checker for the first time, (c) incorporates sensors and noting of the expiration date to verify the efficacy of medications, (d) is not tied to a subscription nor a certain management system such as through a specific hospital or pharmacy, (e) does not require medical professionals, (f) is low-cost. mPillBox introduces a new algorithm that manages the smart pillbox in decision making.

An mPillBox prototype was implemented that includes a mobile application and a smart pillbox implemented with a Raspberry Pi 4 Model B. The rest of the paper is organized as follows: Section 2 discusses related work, Section 3 discusses the architecture, Section 4 discusses the implementation, Section 5 discusses the evaluation and results, and finally, Section 6 discusses conclusion and future work.

2. Related work

Previous research has developed multiple forms of smart pillboxes with the same motivation but different purposes. Multiple products and research papers developed smart pillboxes to manage and schedule medication intake (Jonah Comstock, 2013; AdhereTech, 2023; Abiogenix, 2023; MedSignals, 2023; e-pill Medication Reminders, 2023; Tricella Inc., 2023; PillDrill, 2023; pillohealth, 2022; elliegrid, 2023; Hart Medical Equipment, 2023; Tinylogics, 2023; David Chandler, 2008; CI, 2022, 2021a,b; Abbey et al., 2012a; Srinivas et al., 2018; Rao et al., 2020; Prasath et al., 2021). These systems generally alert the user with LED indicators and audible reminders and connect to smartphones via mobile applications. These applications can send notifications to the user, automatically text or call from a list of user-defined numbers, and track medication usage. However, these solutions have predefined pillbox sizes, provide specific closed-source hardware and software, and in many cases, require setup and input from a health professional. Solutions that must be programmed by healthcare professionals (Abdul Minaam and Abd-ELfattah, 2018; Abbey et al., 2012b) generally require training and coordination between these healthcare professionals.

One solution includes its own internal cellular modem that updates servers of dosage activity and automatically calls or texts caregivers (Medminder Systems, Inc., 2023; Thales, 2022). While this solution does not require internet access, it requires a monthly subscription and does not work outside the United States. A low-cost solution (da Silva et al., 2019) also uses a Raspberry Pi, but unlike mPillBox it requires cloud infrastructure, and simply focuses on scheduling and managing medication intake as is the case with most solutions.

Research in wearable devices requires users to wear a device, for example, to monitor their medication habits and intake (Yang et al., 2014; Rosner et al., 2015; Kumar et al., 2021). These devices are invasive and add a burden on the user. They are also hardware-specific and their use must be coordinated with healthcare professionals. Other smart pillboxes are more concerned about preventing medication abuse while monitoring medication intake (Huang et al., 2014; Khedkar et al., 2018; Kanhasinwattana et al., 2020; Wu et al., 2015; Rosli and Husaini, 2018). These pillboxes use a dispensing mechanism based on timers and previous user medication intake. Another category of smart pillboxes focuses on patient identification and recognition to avoid users taking the wrong medications (Crema et al., 2015; Nijiya Jabin Najeeb et al., 2018).

Few research solutions focus on medication errors (Silva et al., 2013; Wang et al., 2009; Zao et al., 2010; Tsai et al., 2011). SapoMed (Silva et al., 2013) is a mobile application that tracks and manages all prescribed medication. SapoMed does not utilize a pillbox, relies on a specific government database, and relies on local medication barcodes, limiting its use. Wang et al. (2009), Zao et al. (2010) is also a mobile application that sends reminders about medication intake but does not utilize a pillbox. Wedjat creates a framework for checking against medication interactions by relying on existing healthcare infrastructure in the United States. To recognize medication interactions for prescribed medications for a user, Wedjat requires integration into the healthcare system and uses a personal health record system that requires the user to carry all their records. However, this system is not widely adopted (Showell, 2017). A specific smart pill dispenser (Tsai et al., 2011) relies on a medication authoring tool (Yeh et al., 2006) used by some hospitals and pharmacies to check for medication interactions. This pill dispenser relies solely on the prescriptions available via the medication authoring tool. This tool must be supported by the hospital or pharmacy. The burden falls on the user to transfer the file from the tool used by a hospital or pharmacy to the pill dispenser device. This system for the pill dispenser only considers prescribed medications and requires interaction from the hospital and pharmacy.

Existing solutions can require sharing private patient data with third parties. This requirement exposes patient data to security breaches. Research such as IDSIoT-SDL (Wani et al., 2021) aims to create an intrusion detection system for the Internet of Things using a deep learning classifier to protect against Internet of Things attacks. Other research projects create better ciphers to increase security of sensitive data (Verma et al., 2022), use unique markers like deoxyribonucleic acid (DNA) to generate passwords for encrypting user data (Namasudra et al., 2020), use unique forms of authentication through watermarking (Gutub, 2023), or present a new user authentication scheme to prevent unauthorized access to a private healthcare system featuring data from patients and their Internet of Things devices (Das and Namasudra, 2022). Broader projects aim to protect general data through a new access control scheme (Namasudra et al., 2014) or utilizing machine learning for network security situational awareness (Chen, 2022). All of these solutions highlight an ongoing risk of security breaches in the healthcare system and beyond. Patients are left vulnerable to these system attacks, which in some cases might cause death due to unauthorized and malicious manipulation of patient data (Das and Namasudra, 2022).

mPillBox's goal is to provide a system that manages and tracks medication intake and verifies medications with respect to the expiration date and medication interactions. mPillBox does not rely on custom hardware or software supported only by a company or healthcare service. mPillBox also does not restrict the user to a single health provider nor does it require sharing of private data with any provider or healthcare personnel. While the mPillBox prototype uses a specific pillbox layout, the user can deploy mPillBox on any pillbox layout of their choosing. mPillBox provides a mobile application that lets the user easily add to their medication schedules and track medications and their intake while providing reminders beyond simple alarms and notifications.

3. Architecture

mPillBox involves four major components, as shown in Fig. 1. First, the novel algorithm that defines the objective for all components. Second, the pillbox without any additions. Third, the device added to the pillbox. Fourth, the mobile application associated with the pillbox equipment. These four components are integrated to address the following key challenges: (a) Maintaining a schedule of medications and alerting the user when the time is appropriate for taking the medications, (b) Alerting the user to medication interactions, non-ideal atmospheric conditions for the pillbox, or in case of any expired medications, (c) An easy-to-adopt open framework for applying these tools to any pillbox of any shape or size, without requiring the sharing of private health information or the assistance of technical or medical professionals.

3.1. The algorithm

The novel algorithm listed in Algorithm 1 shows a unique automated method to check the validity of newly added medications and their environment. The algorithm accepts a *newMedication* object that contains the medication name, expiration date, and ideal storage conditions if they are different from the standard conditions, timings, and dosage. First, when a new medication is added to the existing system, the algorithm checks the atmospheric conditions before allowing the addition. Second, the expiration date is checked. Third, using the existing interactions checker subcomponent, the newly added medication is checked against interactions with existing medications. In some cases, medications may interact within a certain period of time. This is checked in the next function call, which also checks for any irregularities in the medication timing and dosage. Finally, the algorithm reviews all the checks, reports an error with the reason or proceeds to add the new medication to the existing medication list, and sets the relevant alerts and notifications.

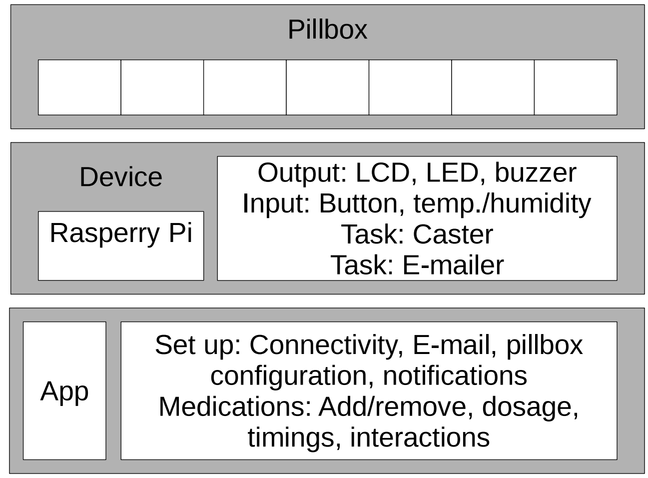


Fig. 1. mPillBox architecture.

Algorithm 1 mPillBox Algorithm

```
function UpdateMedications(newMedication)
    medList ← GetMedicationsList()

    CheckAndReason ← Return values from:
    CheckHumidity(newMedication)
    CheckTemperature(newMedication)
    CheckExpiration(newMedication)
    CheckInteractions(medList, newMedication)
    CheckTimeDose(medList, newMedication)

    if Check == NoError then
        AddToMedicationsList(newMedication)
        SetAlertsNotifications(newMedication)
    else if Check == Error then
        RaiseException(Reason)
    end if
end function
```

3.2. The pillbox

Numerous shapes and sizes exist for pillboxes. Many pillboxes are rectangular while some are available in a circular shape. The sizes of pillboxes also depend on the usage, based on timing and frequency. Some pillboxes are used for per-day usage, others are larger for supporting per-week or per-month usage. Requiring the modification of existing pillboxes to fit a device or mobile application is not user-friendly. Instead, mPillBox allows the user to select whatever pillbox is useful to them. The device simply accompanies that pillbox, and the mobile application gives an option to define the size and shape of the pillbox.

3.3. The device

Using a Raspberry Pi Model B and a general-purpose input/output (GPIO) expansion board, mPillBox implements a device to be placed next to any associated pillbox. This device aims to schedule medication timings and intake, monitor atmospheric conditions for the pillbox, and alert the user through various ways when medication intake is due.

To achieve this, mPillBox adds components to the Raspberry Pi's GPIO expansion board. There are three output and two input components. mPillBox alerts the user visually and audibly through an LED

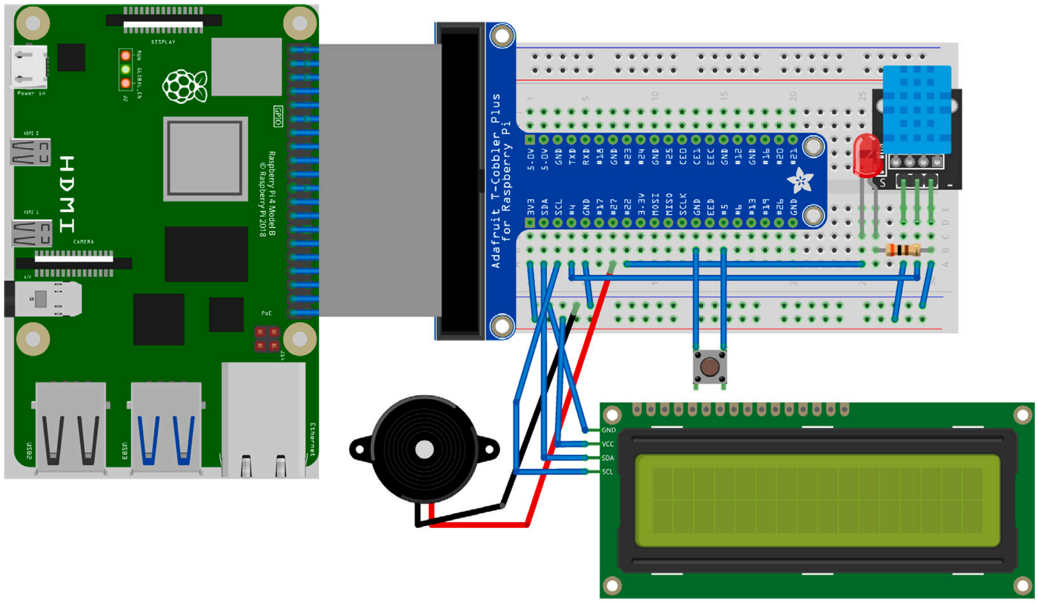


Fig. 2. Fritzing diagram of the device and circuit.

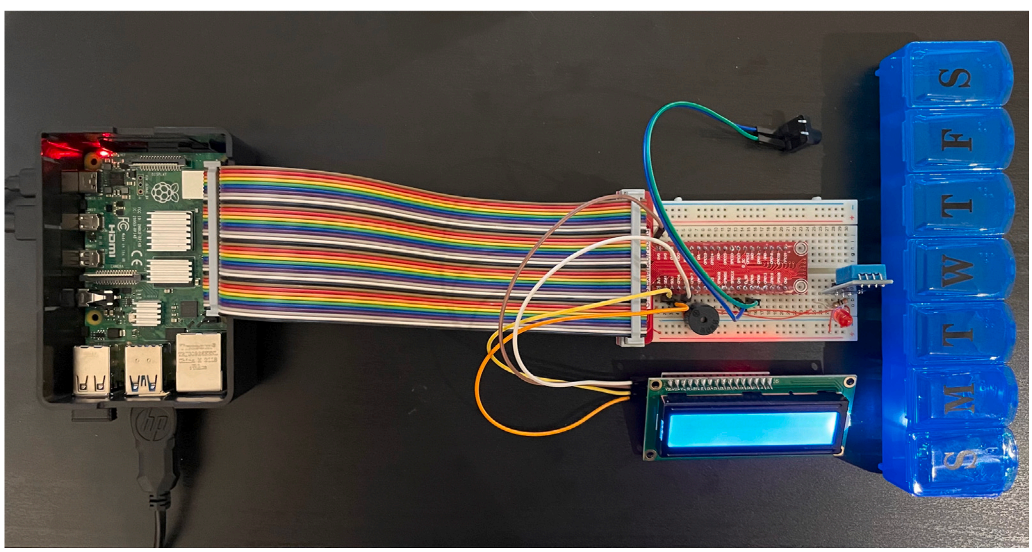


Fig. 3. mPillBox with the device and pillbox.

and a sound buzzer. Additionally, mPillBox provides a third output, through an LCD, to display relevant information about the medications and intake. To monitor conditions around the pillbox, a combined humidity and temperature sensor is added as an input. This enables mPillBox to monitor the conditions around the pillbox directly and in real-time. Finally, in the case an alert occurs, mPillBox gives an option for the user to stop the alert when they reach the pillbox. This input is a tactile push button switch, once the user physically presses the button, the alert is disabled until the next alert occurs. Through this set of outputs and inputs, mPillBox enables the user to interact with the pillbox without restricting the user to a simple non-digitized pillbox or a mobile application.

Fig. 2 shows the Fritzing (2023) diagram for the circuit with these input and output components on the breadboard. The LED requires a resistor to limit the current it draws from the Raspberry Pi. The LED is connected to an output data pin on one side and through the resistor on the other side. The resistor is connected to ground. The buzzer, shown as the large black circle on the left of the LCD, connects to ground and a data output pin. The push button is connected to ground and a data input pin. The humidity and temperature sensors shown in the small light blue component require voltage, ground, and a data input pin. Finally, the LCD, via the I2C module, requires ground, voltage, serial data, and serial clock pins. The circuit components use a shared voltage and ground bus strips on the breadboard. The data input and output pins are not shared. These components do not need to be strictly organized in the shown manner, they may be rearranged in the circuit. Fig. 3 shows the actual device next to a weekly pillbox.

To interact with the available sensors and components, mPillBox runs a background application within the Raspberry Pi. This application initially interacts with the mPillBox mobile application through Bluetooth to either stay in Bluetooth mode or hand off the connection to the same local WiFi network. The application, aside from setting up the Raspberry Pi, runs eight main tasks: (1) LCD task to display relevant information (2) LED task to light up intermittently during alerts (3) Sound buzzer task to buzz intermittently during alerts (4) Humidity and temperature task to monitor the atmospheric conditions around the pillbox (5) Tactile push button switch to acknowledge and stop an active alert (6) Casting task that searches the network for casting devices to cast to during alerts (7) E-mail task to E-mail a list of users ten minutes after an alert occurs (8) A main task that checks all the inputs and updates all of the outputs depending on given parameters and alerts. mPillBox uses a list of user-provided E-mails for notifying their relatives or friends instead of phone numbers and SMS. This design choice is preferable since it requires less setup, is free, and is more accessible (Tony Bradley, 2012). Regardless, an additional task may be added to mPillBox using existing APIs that support automated SMS (Twilio Inc., 2023).

The main task is ultimately responsible for alerting the user when medication intake is due, when medication expires, when there are medication interactions, or when conditions are not ideal for the medications in the pillbox. Given that some users might not have their smartphones nearby and might not be near their pillboxes, mPillBox implements a new feature of using cast-enabled devices. This feature is not explored or available in any digitized pillbox. mPillBox searches for Chromecast (Google Inc., 2023) enabled devices which include speakers, monitors, and televisions. Once mPillBox finds a list of those devices, it round robins through devices to stream an mPillBox video, where applicable, with audio that alerts the user to attend to their pillbox. Users are able to exclude explored devices on the network by blacklisting them in the mPillBox mobile application.

3.4. The mobile application

To allow users to set up the pillbox and interact with the mPillBox device, a mobile application is provided. Upon installing this application, the user is able to set up connectivity, choose the shape and size of the pillbox, and add or remove medications. The user can then perform several tasks such as: Receiving notifications, canceling alerts, changing medications or timings, checking medication information such as expiration dates or medication interactions, setting up a list of E-mails to notify in case of an alert, and be able to enable or disable a device on the list of casting devices available. Fig. 4 shows a flow chart of the mobile application starting from installation to alerts.

After the initial installation of the mobile application, the user is asked to connect to the Raspberry Pi via Bluetooth. Once the Bluetooth connection is made, the user is asked whether to only connect via Bluetooth or to provide local WiFi credentials to connect to the Raspberry Pi. If the user opts for a local WiFi network, a unique token is shared and the IP address and hostname are both noted within the application. Alternatively, mDNS (Internet Engineering Task Force (IETF), 2013) is used to discover the Raspberry Pi on the local WiFi network. The unique token exchanged via Bluetooth is used to identify the exact Raspberry Pi used in the setup. The order of operations guarantees that the user is minimally involved in the setup process for connectivity.

Once the Raspberry Pi is connected, the mobile application asks the user to input a list of user E-mails to message in case of an alert and to disable or blacklist any of the casting-enabled devices found on the network. Next, the user is asked to select the shape and size of the pillbox. The user can then add individual medications to each virtual pillbox slot on the application. Each virtual pillbox slot can carry multiple medications. Aside from the name of the medication and dosage, the application asks for the expiration date and the timing of the medication. The timing can be set to every N hours, daily, specific days of the week, weekly, or monthly. When any medication is due, the correct pillbox slot is highlighted in the application with the name of the medication and dosage shown. This information is also sent to the application on the Raspberry Pi. Note that mPillBox makes the assumption that the user places the correct medications and dosages in each slot.

Alerts are sent to the mobile application in the form of notifications and the Raspberry Pi alerts the user through the output components. These alerts are shown when a medication is nearing the expiry date or when it has already expired, when medication is due, or when there is a medication interaction. The user can directly cancel alerts via the mobile application or by pressing the push button switch on the Raspberry Pi.

The mobile application provides a search list of medications and checks for medication interactions by connecting to public databases that contain medication and drug interaction information. When users finish adding medications, mPillBox goes through the drug interaction databases and lists the medication pairs that include moderate or more serious drug interactions. The user can temporarily check if a non-routine medication interacts with the current set of medications in the pillbox. This allows a user to also verify that they are able to safely take any food items or over-the-counter drugs.

4. Implementation

mPillBox runs on Raspberry Pi OS (Raspberry Pi, 2023) and implements the application on a Raspberry Pi with the WiringPi (Gordon Henderson, 2023) C library to access the GPIO pins. The I2C and SPI interfaces are both enabled for the Raspberry Pi. Each task, detailed in Section 3.3, uses pthreads with the exception of the main task that runs on the main thread. For each task, delays are added and while conditions and parameters are checked for each task.

For the atmospheric conditions, the task ensures that the pillbox is kept in a cool and dry place, as recommended for the vast majority of medications (MedlinePlus, 2023). This means that the temperature should be around 20 degrees Celsius, with a ten percent margin, and humidity should be below 60%.

For the casting task, mPillBox uses the *CATT* (Stavros Korokithakis, 2023) command to scan devices, cast an alert, and stop casting. *CATT* uses a Python library to communicate with Google Chromecast. For the E-mail task, mPillBox uses a free E-mail service to send the messages (Mailjet Inc., 2023). Advanced settings are available on the mobile application for the user to specify their own E-mail account and service. Note that the E-mails sent only alert the recipients and do not mention any details regarding the medications or the dosages for privacy reasons. To automatically connect the Raspberry Pi with the device running the mobile application, mPillBox relies on the BlueZ tools package (BlueZ Project, 2023). WiFi credentials, if applicable, are sent via Bluetooth and stored on the Raspberry Pi for automatically connecting to the local WiFi.

For the iOS mobile application, Swift (Apple Inc., 2023) is used. An application with the same functionality can be designed and implemented for Android. The mobile application uses the National Library of Medicine (National Institutes of Health) HTTP APIs (National Library of Medicine, 2023) to retrieve authentic data on medication and drug interactions. These APIs rely specifically on ONCHigh (Phansalkar et al., 2012) and DrugBang (DrugBank, 2023) for drug interaction information. Other public databases (Drugs.com, 2023b; RxList, 2023) are also available via HTTP for retrieving medication and drug interaction information for mPillBox. The local timing is used, in case of a regional change, such as when a user travels, the timing is accordingly adjusted.

Information is exchanged between the mobile application and the Raspberry Pi device using Bluetooth or, in case it is on the local WiFi network, TCP.

The circuit uses a generic buzzer, a red LED light, a push button, and a 300 ohm resistor. The humidity and temperature sensor used is a DHT11. A 16 × 2 character LCD with a built-in I2C module is used and operates on three volts provided by the Raspberry Pi.

5. Evaluation

To demonstrate mPillBox's usefulness, screenshots are shown of the mobile application, performance is measured on the Raspberry Pi, and an Institutional Review Board (IRB) usability study is conducted. The IRB study is officially reviewed and approved with the consideration

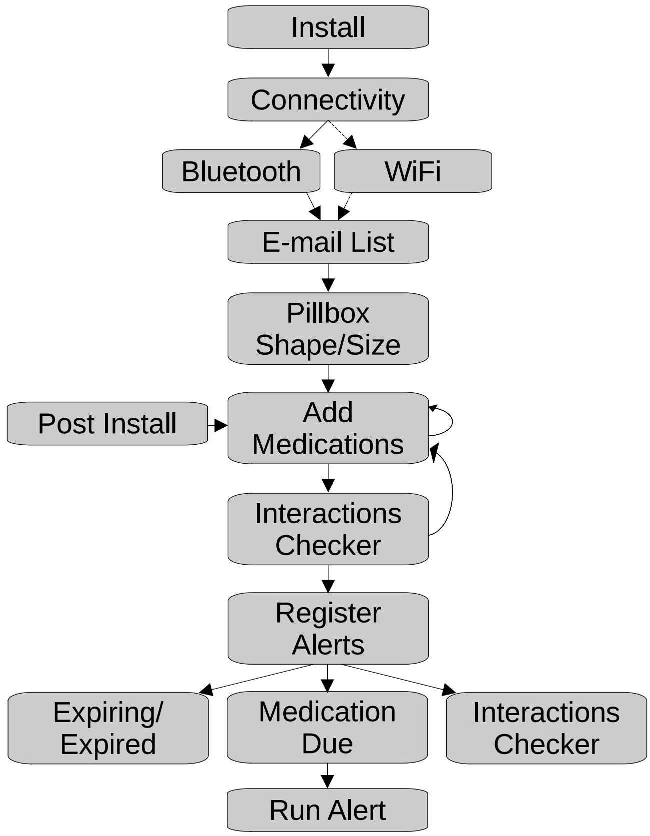


Fig. 4. mPillBox mobile application flowchart.

of the welfare and rights of human subjects. Components used for mPillBox are also listed along with their cost to show that mPillBox is not only efficient but cost-effective. Finally, mPillBox is compared against existing relevant solutions such as digital medication trackers, medication schedulers, and pillboxes. mPillBox runs an iOS prototype mobile application on an iPhone XS running iOS 15.5. The device application runs on a Raspberry Pi 4 Model B (8 GB) with Raspberry Pi OS (Linux raspberrypi 5.15.32-v7l+).

5.1. Mobile application

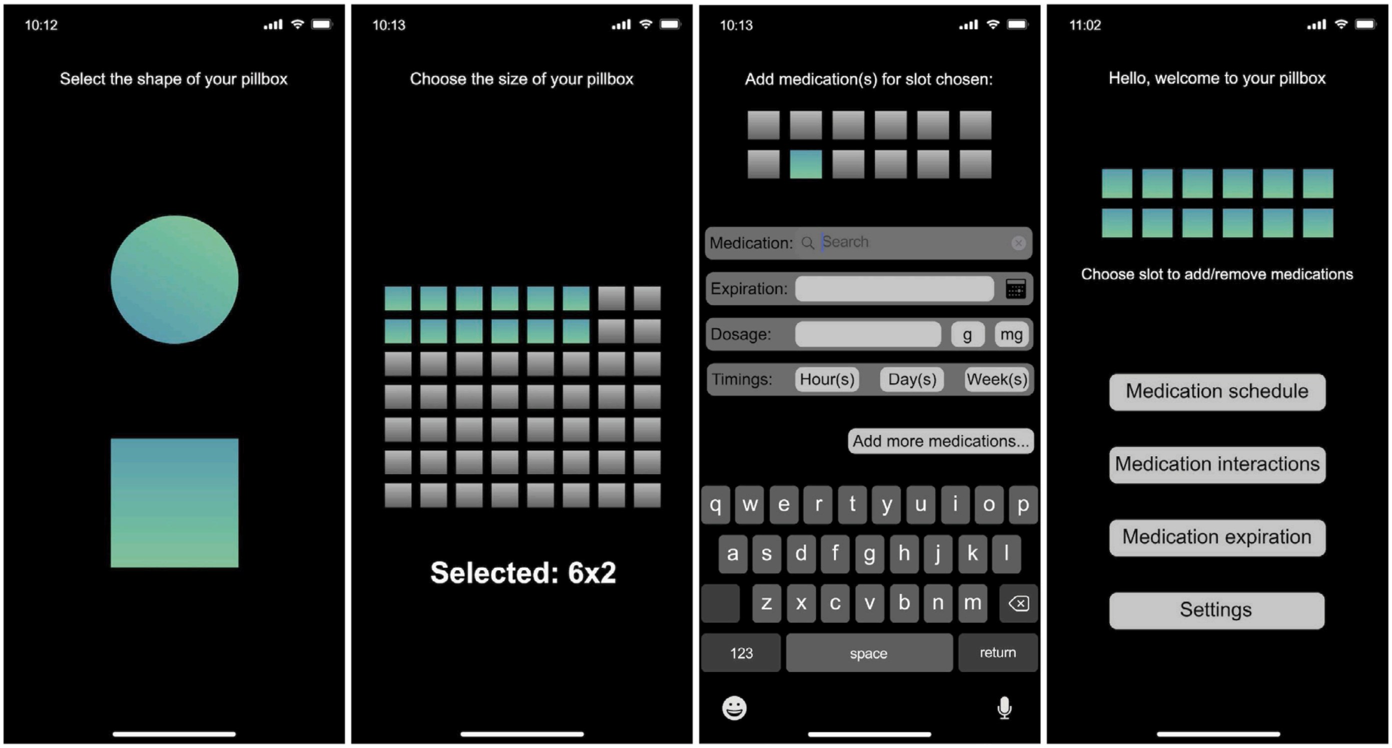
Fig. 5 shows the screenshots of the iOS mobile application prototype. After setting up the Raspberry Pi's connectivity via the application, the user is presented with a setup view, shown in Fig. 5(a), for choosing the shape of the pillbox, either a circular or rectangular shape. Once the shape is chosen, rectangular in the case of Fig. 5(b), the user can tap or tap and drag to select the size of the pillbox. After selecting the size, the user can add medications by tapping on individual pillbox slots, as shown in Fig. 5(c). To add medications, the name can be dynamically searched through a list. The dosage, grams or milligrams, and the expiration date are both required. The user may define a recurring time for the medication per hour, day, or week. For example, the user may take the medication every twelve hours, every three days, or twice a week. All of these options can be selected via the hour, day, or week buttons. The user is alerted if there is a medication interaction or if the medication is successfully added. Once the information for the medication is filled out, the user can keep adding more medications in the same slot, choose another slot, or select the main menu from the medication addition confirmation alert dialog.

The final view, shown in Fig. 5(d), is the main menu view for the application. The first option allows the user to check the medication schedule in a calendar view and modify it by adding or removing medications for each slot. The second option provides a medication interactions checker. This checker allows the user to check existing interactions or check medication interactions for future medications that are not yet in the pillbox. The third option shows the expiration dates for the existing medications in the pillbox and a countdown to the number of days or months until expiration. The final option allows the user to access the settings menu to manage the connectivity for the Raspberry Pi device, the casting list, the E-mail list, and more.

Fig. 6 shows the various alerts shown in the application. The user can dismiss the alert dialog and disable the alert on the Raspberry Pi device by selecting "OK" or the user can dismiss the alert dialog but keep the alert on the Raspberry Pi device. The latter option is helpful in that it requires the user to get to the pillbox to disable it manually via the push button. Note that, in addition to these application alerts, notifications are also used.

5.2. Benchmarks

To evaluate mPillBox, the CPU and memory usage of the mPillBox process is measured on the Raspberry Pi for when mPillBox was idle and then during an alert. First, the CPU usage is monitored and averaged over a period of one minute using the *top* command. The CPU usage on average was 0.5% when mPillBox was idle and around 1.3% during an alert. This shows that mPillBox does not incur any significant CPU overhead. Second, the virtual memory used was measured, using the *pmap* command, as an upper limit for what the process consumes in terms of memory. The memory usage was around 53MB, including shared memory areas, and the actual resident set size was closer to 1.6MB. This shows that mPillBox does not have high memory demands. Given these numbers, mPillBox can easily and efficiently run on the most basic Raspberry Pi models.



(a) App. setup (b) Pillbox size (c) Adding meds. (d) Main menu

Fig. 5. mPillBox mobile application.

Table 1
mPillBox usability questionnaire.

Question	Yes (five users)	No (five users)
Do you need help remembering and managing medications?	✓	
Do you know the expiration dates of your medications?		✓
Do medication interactions concern you?	✓	
Do you find the mPillBox iOS application easy to use?	✓	
Do you find the mPillBox iOS application useful?	✓	
Would you rely on mPillBox to manage your medications?	✓	

5.3. User study

An IRB-approved (KU-COS-22-07-20) user study and questionnaire were conducted to evaluate the usability of mPillBox. There were five users, three technical users, aged 36–38, and two are not, aged 66 and 79. All users relied on medications. The users were presented with the mPillBox device and the mobile application prototype. First, the purpose of mPillBox is explained. Second, how to set up the device with the application is shown. The users were then acquainted with the features of mPillBox. The users were asked three preliminary questions and three follow-up questions listed in Table 1.

The users were first asked if they needed help remembering and managing their medications. All users agreed they do need help remembering and managing their medications. All users were not aware of the expiration dates on their medications, with one user mentioning it is not relevant to them as they use up all their medications before the next batch is provided. All users were concerned about medication interactions and preferred an automated way to check their current and future medication interactions.

The follow-up questions were asked after the users were presented with the prototype and acquainted with the features. The users were asked if they found the application easy to use. They all agreed it was easy to use. Note that one non-technical user required supervised assistance from a non-medical professional to help set up mPillBox.

Table 2
Cost breakdown for mPillBox components.

Component	Price (USD)
Resistor	0.01
LED	0.03
Push Button	0.10
Buzzer	0.18
Board	0.68
DHT11	1.13
LCD	2.75
GPIO Cable & T-Cobbler	3.75
Total	8.63

Despite that, all users found mPillBox useful. Their answers ranged from useful to extremely useful. One user mentioned that the more medications they have, the more they think mPillBox would be useful. All users agreed that they would rather rely on mPillBox to manage their medications.

5.4. mPillBox cost breakdown

To show that mPillBox is indeed a low-cost and affordable system, Table 2 shows a list of components and their prices. The prices, listed

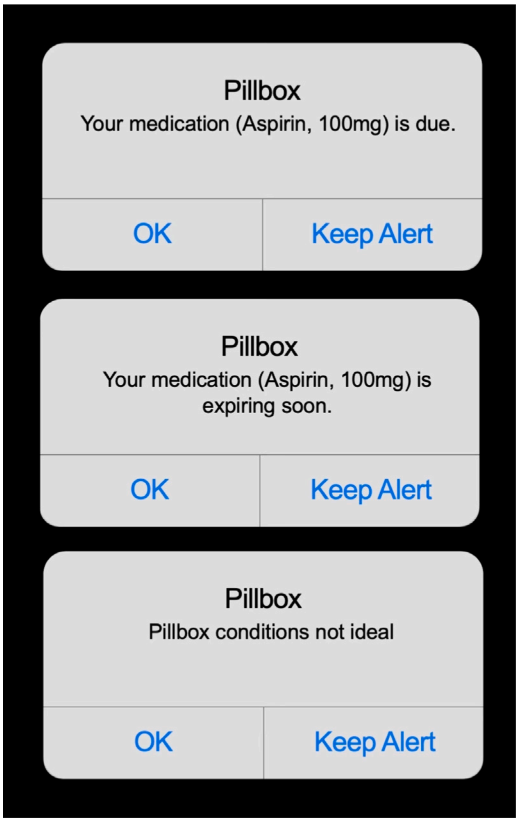


Fig. 6. Examples of mPillBox application alerts.

in United States Dollars (USD), are taken from an approved Raspberry Pi reseller (Cytron Technologies, 2023). The value of mPillBox components amount to less than ten USD. The Raspberry Pi 4 ranges from 35–75 USD. However, as shown in Section 5.2, mPillBox can run on the lower-end models of Raspberry Pi. The total cost of mPillBox amounts to less than the vast majority of existing solutions.

5.5. mPillBox versus other solutions

To show how mPillBox provides a more complete and open system compared to existing solutions, all the relevant features are listed in Table 3. First, comparing mPillBox with other solutions, Table 3 lists if a mobile application is provided. Second, if a subscription is required to use the solution. For example, some solutions require a monthly fee or require the user to be in a specific country. Third, if a solution checks or verifies the expiration date for medications. Fourth, if a solution checks the atmospheric conditions for the pillbox. Fifth, if the solution uses a pillbox or not. Sixth, and related to the previous feature, if a solution uses a pillbox of a fixed, predefined, size or not. Seventh, if it requires any medical or technical professionals to set up. Eighth, if the solution is an open framework, referring to both software and hardware. For example, some solutions manufacture their own pillboxes and some solutions use proprietary or specific software. Ninth, if the solution is a low-cost solution. Finally, if a solution checks for medication interactions or not.

Table 3 shows that the majority of solutions do provide a pillbox. However, almost all of these solutions only provide a pillbox of a specific size. This predefined size might not meet the needs of many users. mPillBox allows users to use their own pillbox with the size of their own choosing. Although the majority of solutions do not require subscriptions many do require assistance from medical or technical professionals. mPillBox does not require a subscription nor assistance from medical or technical professionals to use it, allowing it to be more usable by the general population. Furthermore, mPillBox and many solutions rely on mobile applications to make the process of taking medications easier and more manageable for users. Note that the majority of solutions are only concerned with reminding users to take their medications without focusing on an important aspect of effective medications. In particular, the medications cannot be expired or subjected to non-ideal conditions such as high temperatures or humidity. mPillBox is the only solution in Table 3 that tracks medication expiration dates and takes pillbox conditions into account. In addition, almost all solutions do not inform the user if there are medication interactions given their medications and schedule. mPillBox focuses on these crucial aspects for avoiding medication errors.

mPillBox is one of only three systems that provide a low-cost solution. Additionally, mPillBox is the only open framework solution for a smart pillbox. Given that mPillBox is a low-cost and open framework, both its software and hardware can be obtained to provide mPillBox to the masses. mPillBox would also be useful in remote areas or developing nations as it does not require a subscription, cloud infrastructure, or any professionals to manage it.

6. Conclusion and future work

mPillBox is an open and low-cost framework for making a pillbox smarter. mPillBox uses a Raspberry Pi and a circuit to be attached to any pillbox, of any shape or size, to monitor its atmospheric conditions and to provide visual and audible alerts to the user. Unlike existing solutions, mPillBox ensures that medication errors are avoided by making sure medications are not expired and are effective through a novel algorithm. mPillBox also provides an automatic medication interactions checker to avoid adverse effects. In case of any issues, mPillBox allows the user to rely on Internet of Things devices in the vicinity to alert the user. mPillBox is designed as a low-cost open framework system, with no subscription fees and without requiring medical or technical professionals to set up. This allows mPillBox to be easily deployed in many regions. An mPillBox prototype was built with an iOS application that allows the user to choose their pillbox shape and size and schedule their medications per slot. The results show that mPillBox is low-cost, user-friendly, preferable for users, and a better smart pillbox model compared to existing solutions. For future work, incorporating machine learning for the medication interactions checker or optimizing the medication schedule for maximum efficacy and convenience for the patient should be explored. Additionally, a large scale study could be deployed to explore mass scale adoption.

CRediT authorship contribution statement

Naser AlDuaij: Conceptualization, Data curation, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Table 3
Comparison of mPillBox with other solutions.

	Mobile app.	Subscription not required	Expiration	Pillbox conditions	Pillbox	Any pillbox	Professionals not required	Open framework	Low cost	Medication interactions
mPillBox	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Medminder Systems, Inc. (2023), Yang et al. (2014), Rosner et al. (2015)					✓					
Wang et al. (2009), Zao et al. (2010)	✓	✓								
Tahir (2015), Abbey et al. (2012a), David Chandler (2008), Huang et al. (2014), Khedkar et al. (2018)		✓			✓					
Hayes et al. (2006)					✓	✓				
AdhereTech (2023), MedSignals (2023)					✓		✓			
Tsai et al. (2011)					✓					✓
Rao et al. (2020), Abbey et al. (2012b), Kanhasinwattana et al. (2020), Rosli and Husaini (2018), Crema et al. (2015), Nijiya Jabin Najeeb et al. (2018)	✓	✓			✓					
Silva et al. (2013)	✓	✓					✓			
Jonah Comstock (2013), Abiogenix (2023), elliegrid (2023)	✓				✓		✓			
e-pill Medication Reminders (2023), pillohealth (2022)		✓			✓		✓			
Srinivas et al. (2018)	✓	✓			✓	✓				
Tricella Inc. (2023), PillDrill (2023), Hart Medical Equipment (2023), Tinylogics (2023)	✓	✓			✓		✓			
Wu et al. (2015)		✓			✓		✓		✓	
da Silva et al. (2019)	✓	✓			✓	✓	✓		✓	

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