An Automatic Medication Self-Management and Monitoring System for Independently Living Patients

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Abstract—**This paper describes the development, prototyping, and evaluation of RMAIS (RFID-based Medication Adherence Intelligence System). Previous work in this field has resulted in devices that are either costly or too complicated for general (especially elderly) patients to operate. RMAIS provides a practical and economical means for ordinary patients to easily manage their own medications, taking the right dosage of medicine at the prescribed time in a fully automatic way. The system design has the following features: (1) fully automatic operation for easy medication by using the built-in scale for dosage measurement and a motorized rotation plate to deliver the right medicine container in front of a patient, (2) various medication reminder messages for patients, and noncompliance alerts for caregivers (such as doctors, relatives or social workers who take care of the patients), and (3) incremental and economical adoption by pharmacies, patients, and insurance companies.**

I. INTRODUCTION

According to the national council report [1], “In the United States and around the world, there is compelling evidence that patients are not taking their medicines as prescribed, resulting in significant consequences.” A large percentage of patients fail to comply with their prescribed medication schedules [2][3][4]. This can result in unnecessary disease progression, complications, lower quality of life, and even mortality.

This growing trend of medicine nonadherence has many causes [5][6][7]. “The most commonly cited reasons for noncompliance include, not being convinced of the need for treatment, fear of adverse effects, difficulty in managing more than 1 dose a day, or multiple drug regimens” [5]. Paper [6] identified that “24% of respondents ascribed nonadherence to forgetfulness. 20% did not take medications due to perceived side effects”. Additionally, it is projected that the population growth of retirement-age Americans will cause the current healthcare system to become overloaded and inevitably fail in as little as ten years [8][9][10]. Although forgetfulness is not the only factor contributing to the medication nonadherence issue, it is the biggest factor, and hence, there is a real need to develop an automatic medication self-management device. In addition, if the device can provide near real-time medication remote monitoring to alert health care providers of nonadherence events, it would also help reduce medication nonadherence caused by the other factors.

Research presented in [11][12] discusses the necessary shift from infrastructure-based to home-based care. The efficiency of home-based care is discussed in [11][13][14], where it is shown that with the appropriate technology, more attention are given to patients compared with a traditional healthcare environment, while greatly reducing their burden on caregivers. This type of passive remote monitoring allows a patient's care to be completely managed by an assistive device, only alerting the caregiver when their attention is required. This greatly increases caregiver efficiency, and effectively increases the patient capacity of the current healthcare system [15][16].

Therefore, there is a growing need and urgency for in-home healthcare devices and technologies in order to provide patients with the electronic tools to support medication self-management. However, there is a lack of research and applications for practical and economical in-home medication self-management systems. Facing this challenge, in this paper we develop a patient-manageable medication administration system called RMAIS (RFID-based Medication Adherence Intelligence System). RMAIS enables patients to follow a complex medication regimen with minimal effort without the active assistance of a caregiver. This should enhance the lives of patients, and enable independent living.

Intel's Proactive Health Lab presented some similar work [14][17]. These papers describe a system that tracks a patient's medicine supply using Radio Frequency Identification (RFID) and a scale. When the patient receives a new medicine, a uniquely identifiable RFID tag is attached to the medicine's container so that the corresponding medication schedule information can be input into the system. The medicine storage device is then able to provide corresponding reminders to the patient. The scale is used to check that the correct dosage is taken. This system succeeds in providing a reminder to forgetful patients; however, it requires patients to manually assign RFID tags to the containers, and manually input schedule information whenever new medicines are added. It also lacks the ability to separate an individual container from the medicine inventory, and the ability to alert a caregiver if dosages are not taken correctly. Without these features, the most critical interactions with the system would likely have to be done by an able caregiver, thus making it unsuitable for independently living patients.

Another problem with the system presented in [14][17] is that the proposed system requires all medicine bottles to be placed on top of a scale in order for the system to measure the total weight of the medicine inventory. This procedure is unsuitable for patients with many medications, and requires a large-size and expensive high-capacity scale. In addition, it requires a patient to manually pick up the right bottle from the cluster of bottles on top of the scale. This operation can be inconvenient and dangerous for a patient who has poor motor skill or vision.

Another prior system, called EMMA, is an FDA approved in-home medication dispenser developed by INRange Systems Inc [23]. It can automatically dispense a given dosage of pills, and alert a patient when it is time to take them. However, EMMA has two major problems. First, all pills need to be individually packed into a proprietary cartridge. This can only be done by medicine manufacturers, not pharmacies. This requires a major change in current medicine distribution chain, greatly increasing the cost of medication, and limiting its adoption to participating manufacturers. Second, it can only be used with pill format medicines, and cannot be used with liquids or any other less common medicine formats. It is important that an in-home medication administration device is compatible with all of the patient's medications. Otherwise, the patient will likely forget about medications that are not automatically managed.

RMAIS presented in this paper fills these functionality gaps. It is built on a mature engineering technology— RFID, which is practical and inexpensive to implement, and already proven in the healthcare industry [18][19][20][21]. Adoption simply requires the addition of a basic RFID writer (around $130 USD) and software at participating pharmacies. Standard RFID tags can be easily integrated into medicine containers, and cost around $0.20 each when purchased in small quantities. RMAIS does not require any other alteration to the current manufacturing and pharmacy operating procedures. Just like the printed label on a medicine container, the data written to its RFID tag specifies the medicine name, schedule, dosage amount, and special instructions.

We have developed a complete prototype of RMAIS, which is described in detail in this paper (the initial preliminary work was published in a conference paper [22]). The proposed system has the following features:

- The system can alert the patient in various ways, such as an alarm sound, cell phone or pager text message, or automatic phone call, when it is the time to take medicine.
- Data on a medicine bottle's RFID tag enables the system to automatically read the medicine's information without requiring manual input from the patient or caregiver.
- With the built-in scale, the system can automatically tell if the patient has taken the right amount of dosage for each medicine.
- With the motorized rotation platform and each medicine bottle's RFID data feedback, the system can automatically position the correct medicine bottle in front of the patient for her to take—there is no need for a patient to decide which bottle to pick among a cluster of medicine bottles.
- With the built-in network interface card, the system can automatically alert the patient's healthcare provider or pharmacist (via email or text message) of overdose or under-dose incidents.

The rest of this paper is organized as follows. In Section II, we present our solution system in detail. In Section III, we evaluate the completed prototype. In Section IV, we discuss additional designs for the system. Finally we conclude the paper in Section V.

II. SYSTEM DESCRIPTION

To deal with the unsolved challenges existing in previous work, we introduce an inexpensive and marketable medication administration system called RMAIS that enables patients to follow prescribed medication schedules without the active assistance of caregivers. A primary design objective of RMAIS is to enable easy usage by ordinary patients who may have limited skills using advanced electronic devices. According to this objective, the medication management system is designed to be fully automatic so requiring minimal operation by a patient. For example, when a patient is alerted by RMAIS to take her medicine, the first medicine to be taken at that time will be automatically rotated to the front section of the device by a built-in motor. Then, the patient simply picks up the container in front of her, takes the dosage displayed on the LCD panel, and places it back down on the device. RMAIS verifies that the correct dosage has been taken via a built-in scale, and automatically rotates the second medicine that should be taken to the front of the patient again, and so on. There is no need for a patient to remember which medicine container should be picked up and how much dosage should be taken. As another example, when a patient brings home a new medicine, she simply places the medicine container on the front section of RMAIS, and the medicine information will be automatically input into the system via RFID communication; no manual input is required.

A. System Architecture

RMAIS in-home device is composed of five parts: the motorized rotation platform, scale, RFID reader, microcontroller, and user interface panel. In order to manufacture the prototype, we used SolidWorks® 3D CAD design software to generate the detailed device model. Fig. 1 shows the prototype assembly with three medicine bottles. All of the transparent parts shown in the figure are made from polycarbonate plastic for easy and fast prototyping. Fig. 2 shows the bird's-eye view with detailed labeling. Fig. 3 shows the photo of the actual prototype we developed.

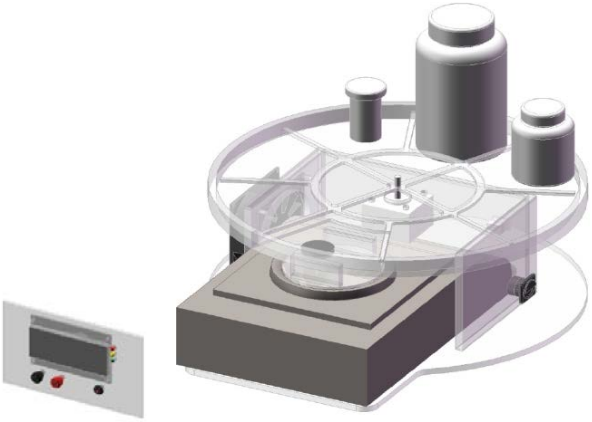


Fig. 1: SolidWorks® assembly model of the prototype RMAIS in-home device. The component on the left-hand side is the LCD display and user interface panel.

1) *Motorized Rotation Platform:* The most innovative design in RMAIS is the motorized rotation platform. As illustrated in Fig. 1 and Fig. 2, medicine bottles are placed on a round, stationary platform with a raised outer edge wall. A raised spoke is placed on top of the platform and fixed to a stepper motor that controls its angular position. With this design, each medicine bottle is confined within each section defined by the spoke and edge wall. For example, the prototype shown in Fig. 1 has 8 sections. Medicines can then be easily pushed by the rotating spoke and slide around on the platform, passing through the special section above the scale for automatic weight measurement of each individual container. We call this section on top of the scale the "*scale-top pan*." The weight measurement operation is very similar to that of trucks at a US highway weigh station (where the truck scale or weigh bridge is built at the same level of ground and permit the trucks to continue driving through while being weighed).

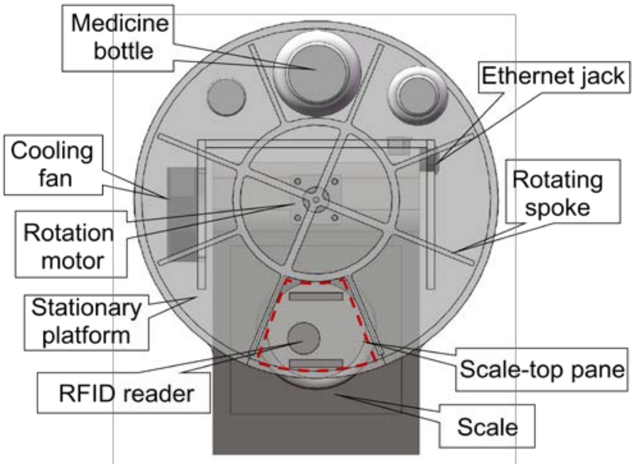


Fig. 2: Bird's-eye view. The small microcontroller and all component wiring are behind the scale, under the rotation step motor.

This novel weighing procedure is a large improvement over the previously mentioned related work [14][17] that uses a single scale to measure all of the medication containers at once. RMAIS allows each medicine container to be identified and weighed one by one in a fully automatic manner. In addition, comparing with the systems presented in [14][17], weighing each medicine container individually allows RMAIS to use a much cheaper scale with a smaller weighing capacity.

In order to weigh a medicine bottle, the scale-top pane is attached to the scale, while being barely separated from the remaining part of the stationary platform (as illustrated in Fig. 4). When manufacturing the scale-top pane, we cut this section out of the larger round piece of the stationary platform, ground off a little bit from the inside edges, and attached it to the scale's measurement tray. We used two rectangular plastic parts to lift it up to the same height as the main stationary platform. In this way, a bottle can be pushed by the rotating spoke and seamlessly slide from the main stationary platform onto the scale-top pane surface. Once on the scale-top pane, it can be weighed by the scale without any interference from the rest of the stationary platform.

Fig. 3: Picture of our actual RMAIS prototype. The LCD panel on the left displays the medicine name and dosage information of the bottle currently on the scale-top pane. The scale has a dimension of 6.8 x 3.7 x 9.8 inches.

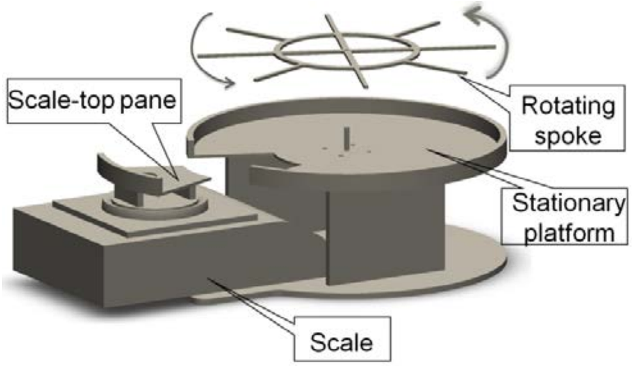


Fig. 4: An exploded model of the stationary platform, scale, scale-top pane, and rotating spoke. When a medicine container is pushed by the spoke onto the scale-top pane, it can be weighed independently from the other containers because this section is physically separated.

2) Scale: The scale is used to weigh individual medicine containers in order to monitor whether a patient has taken the correct dosage. The scale's accuracy should be on the order of milligram because some pill and liquid dosages are as small as just a few tens of milligrams. In addition, it needs to have a communication interface to send weight measurements to the microcontroller. For these reasons, the scale is the most expensive component of the prototype. We purchased the Acculab Vicon Portable Digital Balance VIC-303 and attached RS-232 interface kit [24]. The combined cost is around $350. In future commercial adoption, this cost can be substantially reduced by developing a custom scale for mass production, which will be further discussed in Section B.

3) RFID Reader/Writer: There are many types of RFID tags available with different wireless transmission ranges, frequencies, sizes and costs. Our requirements are low cost, passive tags that have a small amount of data storage for medicine information, and can be easily attached to medicine containers. Since we do not require a long transmission range, very cheap tags can be purchased. For our prototype, we used Texas Instruments (VA) 13.56MHz RFID Transponders (Tag RI-I16-114A-01) [25], which cost around $1 per tag. The cost is high because we only purchased a few tags. In mass production, the price of each tag could be as low as 5 cents [26]. These tags are the shape and size of a US quarter coin, and are as thin as normal print paper. This enables us (or a pharmacist) to easily paste a tag onto the bottom of each medicine container until a permanent solution is developed.

Over-the-counter medicines can also be used in RMAIS. When patients pick up their over-the-counter medicines, they could bring those medicines to in-store pharmacy and then a pharmacist could manually attach corresponding pre-prepared RFID tags to these medicines.

For the RFID reader, we purchased a small (25.4mm diameter) 13.56MHz reader manufactured by Skyetek Inc. [27] (shown in Fig. 5). The RFID reader is attached to the scale-top pane in order to identify a medicine container residing above it. The SkyeModule M1-Mini has a read range of around 3 to 4 cm. It is compatible with our RFID tags, and can be integrated into a shallow hole at the bottom-side of the platform surface of the scale-top pane as shown in Fig. 2. With this setup, there is a 1 to 3 cm distance between the RFID reader and the tag on the bottom of a container positioned on the scale-top pane. This allows the reader to reliably read and only read the tag of the bottle on the scale-top pane without the need to consider possible interferences from the RFID tags of other containers on the stationary platform.

Fig. 5: The small RFID reader is integrated into the bottom-side of the scale-top pane for reading medicine identification and dosage data. It is only 25.4mm in diameter and 2.8mm in height.

In order for the device to work at a patient’s home, cooperation at the pharmacy is required to store prescription information on each medicine container. This is done by the simple addition of an inexpensive RFID writer to the pharmacy’s current computer system. The information stored on a medicine bottle’s RFID tag is a subset of the information printed on the bottle’s label, and can be written to the tag concurrently by the pharmacy’s computer. The procedure for writing data to the tag is as simple as placing the tag within 6 inches of the RFID writer for less than 1 second. For testing purposes, we used the DLP-RFID1 RFID writer [28] to write data to tags. This RFID writer was chosen because it is compatible with our tags, and has a convenient USB interface to connect to computers. It is also inexpensive with a retail price of only $130.

4) *Microcontroller:* The processing in the prototype is handled by the Arduino Mega [29], a prototyping board based on the ATmega1280 microcontroller. It has all of the required I/O interfaces, and is small enough to fit on the inside of the main chassis behind the scale in our prototype.

We also installed an Ethernet interface [30] to the microcontroller board, enabling Internet access to and from the system. With some simple networking programming, our prototype can send an alert email or cell phone text message to the patient as a medication reminder, or to the patient's caregiver as a noncompliance alert.

5) *User Interface Panel:* The user interface panel consists of three parts: the button array, the LED array, and the LCD panel (picture is shown in Fig. 6). The buttons are used for system operation and navigating menus on the LCD screen. The LED array displays information from the microcontroller concerning the system status. The LCD panel displays information to the patient, including current medicine information, instructions, alert explanations, and system menus. In our prototype, we used a generic white-on-blue LCD display with a retail price of $20.

B. Cost

The estimated total cost of the parts necessary to build our in-home RMAIS device prototype is less than $900. A simplified budget is shown in TABLE 1.

TABLE 1: SIMPLIFIED BUDGET FOR RMAIS PROTOTYPE

Item	Cost
In-home Device	
Digital Scale w/ Computer Interface	$354.95
RFID Reader Circuit	$86.25
Microcontroller Board	$65.00
Network Interface Card	$32.99
Power Adapter	$18.30
LCD Display	$18.00
Stepper Motor	$14.95
Electronic Buzzer	$1.50
Other Electronics	$105.05
Building Materials (estimate)	$164.30
TOTAL	**$861.29**
Pharmacy Equipment	
RFID Writer	$130.49
RFID Tags (x25)	$19.73
TOTAL	**$150.22**

The cost of a mass produced RMAIS in-home device could be reduced significantly from the prototype cost by reevaluating the scale, RFID writer, electronics, and building materials. The scale is the most expensive component of the prototype, representing over 40% of the overall cost. It is expensive because it is a standalone scale designed for general-purpose weight measurement. In mass production, we can design an integrated scale for the in-home device that would be much less expensive to produce, fit the device better, and function better in the typical device environment. For example, the integrated scale does not need the user interface panel that is currently included with the scale we purchased.

In this cost analysis, we have not considered other potential costs such as device maintenance, technical support, upgrades, legal and liability issues, which we believe are out of the scope of this technical research paper.

C. Patient Operation

Patient operation of the prototype is mostly automatic, as it is designed to be unobtrusive by mimicking the traditional medicine taking procedure. In normal operation, no button presses or intentional user feedback is required. For example, to take a medicine, the patient simply picks up the medicine container at the front of the device (on the scale-top pane), takes the dosage shown on the LCD display panel, and replaces it. The next medicine container will then be automatically moved by RMAIS onto the scale-top pane again, and so on. If noncompliance is detected (e.g. the patient forgets to take enough medicine dosage or takes too much), the patient and caregiver are notified audibly, visually, or via cell phone text message. In the following sections, we describe several key patient-device interactions.

1) *Initialization and Adding Medicines:* When a patient initially brings the device home, it needs to be initialized and introduced to all of the patient's existing medicines. RMAIS makes this a very simple step. Once the patient connects the machine to a power and Ethernet line, it will automatically obtain an IP address from a cable modem or wireless router in the same way as a normal computer. The microcontroller uses the network time protocol (NTP) to connect to a predefined time server (there are many free time servers on the Internet), and automatically configures its internal clock.

After the clock is set up, the patient can place the tagged medicine containers onto the scale-top pane one at a time. RMAIS then uses the integrated RFID reader to automatically read each container's tag data, save the medicine information into memory, and then rotate the spoke to empty the scale-top pane for the next medicine container. This procedure requires no manual input from the patient. Once a medicine has been added, the microcontroller's persistent memory is updated, and the caregiver is notified.

RMAIS must maintain an empty scale-top pane to accept medicine container input. If there are n total sections, and $n – 1$ medicines in the medicine database (including medicines temporarily checked out by the patient as discussed in Section 5), new medicines cannot be accepted. In this case, the user interface panel will alert the patient when they try to add a new medicine to a full device.

2) *Taking a Medicine Normally:* When it is the right time to take a medicine, the corresponding container is moved onto the scale-top pane and weighed. Then, the patient is alerted via various ways such as the built-in alarm sound, cell phone text message, or automatic phone call, and the green LED light on user interface panel is lit to indicate that the system is ready to administer medication. Because many elderly patients may be unfamiliar with cell phone and text messaging technology, a dedicated beeper (e.g., a watch-like beeper wearing on a patient's wrist) can be easily substituted to remotely alert a patient.

When the active medicine container is positioned on the scale-top pane, the dosage information is displayed on the user interface panel (as shown in Fig. 6). When the patient picks up the container, the user interface panel acknowledges by displaying a message to replace the container. The patient can then attempt to take the stated dosage, and place the container back on the scale-top pane.

If the patient has taken the right amount of medicine, no further action is required. If more needs to be taken, the display will instruct the patient as to how many more units should be taken until either the patient takes the remaining units, or fails three times. If the patient does not take the right amount of a medicine, the caregiver is alerted via cell phone text message or email, and the display notifies the patient of the failure. In all cases, once a medicine has been administered, its final weight is recorded, and the rotating spoke moves the next medicine that is to be taken at the same time onto the scale-top pane until no more remains. The persistent memory is updated after each medicine is processed.

Fig. 6: Picture of the user interface panel ready to administer a medicine. The LCD screen shows the medicine name, dosage, and special instructions for the medication. It can be designed with a large LCD panel to show very large and bright colored text in order to help vision impaired (such as elderly) patients to read.

3) Idling: When there is no user input and no medicine is to be taken, the prototype remains in an idle state. During this time, the user interface panel displays a screen that says “Ready” and the current time. During the idle state, the system constantly checks the scale-top pane for new medicine to be added to the system, as well as listens for a software interrupt to indicate when it is time to take medicines. Additionally, once per day, the device will re-identify each medicine container on the platform by rotating one round, and add any medicine that is not in its medicine database. This is done in case the patient adds a medicine to the platform, but forgets to check it in via the scale-top pane first. The system will also output its status to a USB connected serial terminal every five minutes. This is useful for software debugging, as well as for a caregiver who wants to check which medicines are enrolled in the device.

4) Taking a Medicine Early: A patient can configure the prototype to allow taking a medicine as early as, for example, one hour, before the scheduled dosage time occurs. When any medicines are to be taken within this time period, the idle screen displays the number of medicines that can be taken, and the green LED is lit. If the patient wants to take a medicine early, she presses the blue button on the user interface panel repeatedly until the desired medicine container is moved onto the scale-top pane, and then presses the red button to begin administration.

5) Checking Out a Medicine: If a patient is able, she has the option to “check out” medicines to take with her while she is away from the device (going on vacation, attending a senior center, visiting her family, shopping, etc.). To check a medicine out of the system, the patient presses the blue button on the user interface panel repeatedly until the desired medicine container is moved onto the scale-top pane, and then presses the red button before taking away the medicine container.

This is the same procedure used when taking a medicine early, so it is important to note that when a medicine is eligible to be taken early, it must be taken before it can be checked out.

6) Taking a Checked Out Medicine: When medicines are checked out of the system, the device will send the patient a text message (or automatic phone call) every time a checked out medicine should be taken. The message contains all of the information normally shown on the user interface panel.

When the patient returns, she simply places the checked out medicines back onto the scale-top pane one by one to check them in again. The device will reweigh each container to make sure that the right amount was taken. If an overdose or under-dose is detected, the LCD panel displays alert messages, and the caregiver may also be alerted. Once the checking is complete, the persistent memory is updated. This function can be disabled for patients who are unable to self-manage medications or have very strict dosage schedules. Fig. 7 illustrates the system functioning at home, remotely communicating dosage instructions and alerts to the patient and the doctor or caregiver.

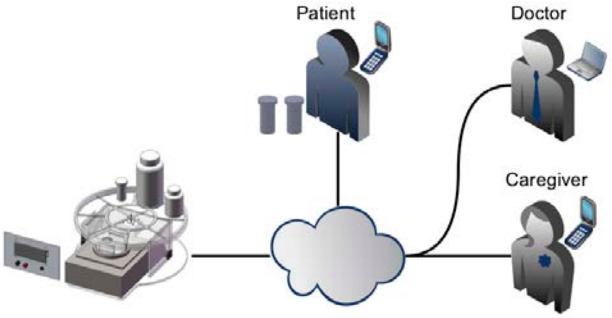


Fig. 7: If a patient is able, she can check out medicines and receive remote reminders to take each one while away from the device. Her compliance is checked when she returns and checks in those medicines.

There are some types of medicines that would be hard for RMAIS to deal with. For example, if a medicine is in foil strips, the weight may be reduced not only by the pill weight but also by, for example, disposal of the foil strip or by bits of foil stripping off as the strip is popped. Such medicines would be hard to use the built-in scale to measure patient in-taken dosage. For such kind of medicines, RMAIS can just track the medicine without using the built-in scale to monitor how much dosage a patient takes. The RFID tag of such a medicine contains a special flag variable to indicate that the medicine does not need weight monitoring.

D.Pharmacy Operation

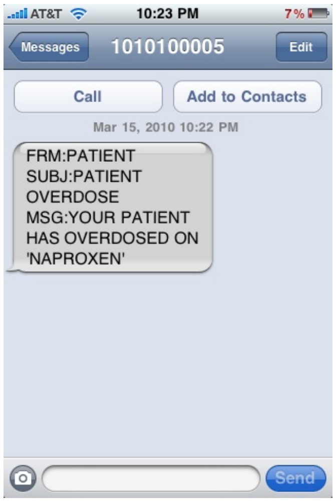
A participating pharmacy needs to adopt two items. One is to connect an inexpensive RFID writer to its current computer and update the computer software. Second is to use medicine containers that have blank small-size RFID tags pasted at the bottom of these containers.

When pharmacist inputs medicine information into her current computer system, she just needs to place the medicine container close to the RFID writer (within 6 inches of the RFID writer for less than 1 second) and the computer will automatically write medication information into the container's RFID tag. It can be completed at the same time when the pharmacist's computer prints out the medicine container's paper label (printing individual drug's label and transferring drugs to standard medicine containers is the standard way for pharmacists in United States to issue most prescription drugs). In this way, RMAIS only adds a small operational burden to participating pharmacies (at least in United State where pharmacies are currently using computer systems to print out medicine labels for individual medicine containers), and can be adopted on a per-pharmacy basis for incremental deployment.

One new datum that needs to be put into RFID tag is the medicine's "pill weight", which is required by RMAIS in order for the device to monitor whether a patient takes the right dosage. Since all medicine manufacturers provide such data along with their produced medicines, the pill weight information can be easily incorporated into a pharmacy's medicine database without much difficulty and cost.

E. Caregiver Operation

Caregiver operation is very simple, and does not require any special equipment. A caregiver's attention is only required when the system is initially set up in order to set the patient and caregiver phone numbers, and adjust the system time zone. From that point forward, whenever attention is required, a text message is sent to the caregiver's cell phone. We have successfully implemented this function into our prototype. Fig. 8 shows an example of an overdose alert message received by a caregiver.



Mar 15, 2010 10:22 PM

FRM:PATIENT
SUBJ:PATIENT OVERDOSE
MSG:YOUR PATIENT HAS OVERDOSED ON 'NAPROXEN'

Fig. 8: Screenshot of a text message received by a caregiver's cell phone.

Our current prototype implements text message and email to inform a patient's caregiver of overdose/under-dose incident. This is the quickest way to let caregiver to monitor medication compliance. However, a doctor could have many patients; too many alert text messages sent to a doctor at once could overwhelm the doctor or interfere with her work or private life. To resolve this problem, we will design a software system that can be run on a dedicated computer server. All RMAIS in-home devices of the doctor's patients connect to this server to report their medication activities, not only medication noncompliance incidents, but more detailed medication information (with the permission from those patients). The medication monitoring software running on the server can judge when it is a good time to alert the doctor.

To enable this networking operation, we need to ensure the data communication from RMAIS devices to the server is secure. Since this networking has standard client-server based architecture, we can directly implement any mature security protocols currently used in the Internet.

F. Software Design

In this section we describe several important procedures and data structures in the prototype software design.

1) *Medicine Counting Algorithm:* The scale is used to weigh medicines to determine how many discrete medicine units were taken. Medicine unit could have various forms, such as tablet for pills, milliliter or teaspoon for liquid medicines. This measurement is done by comparing the weight of the medicine container before and after the patient accesses it, and calculating the number of units based on the weight of one individual unit.

Weight measurements are polled from the scale by the microcontroller. The scale waits to send weight information until a built-in algorithm determines that the platform is stable. Instability is caused by environmental conditions such as the turbulence of the air in the room, or the vibrations caused by the interior cooling fan. Because of the desired milligram-level accuracy, such instability interference cannot be ignored. For each weight measurement passed to the operational functions, the microcontroller takes the average of five stable readings from the scale. Table 2 shows the algorithm used to determine the number of medicine units taken from a given weight displacement.

TABLE 2: MEDICINE COUNTING ALGORITHM

```
counter := 0
X := Weight Displacement
while (X ≥ Pill Weight / 2)
    counter := counter + 1
    X := X – Pill Weight
return counter
```

2) *Medicine Data Retention:* Medicine information is stored on each container's RFID tag, and is tracked by the microcontroller. The tags we used in our prototype have 256 bits of memory space for data storage. The following is a description of data saved on each container's RFID tag.

- **UID:** An eight-byte unique identifier is hardcoded into each tag from the manufacturer.
- **Medicine Name:** Twenty characters of the medicine name are stored as an ASCII value.
- **Medicine Schedule:** A dosage frequency between one and four times per day, the number of units that should be taken at each time, and the weight of an individual unit is stored. As an alternative to a frequency-based schedule, dosage times can be set to a specific time of day. All of these values are stored as integers.
- **Special Instructions:** Special instructions can be assigned to medicines, including "take with food," "take with water," "stay home," and "do not take with Aspirin." Each of these four cases is stored as an integer that is set to 1 for true and 0 for false.
- **Entry Method:** An entry method is assigned. This method can be oral swallow, oral chew, oral liquid, nasal, injection, eye, ear, or anal. This value is stored as an integer between 0 and 7, consistent with the order listed.

3) *Unexpected Input Handing:* Because RMAIS will be used by general patients who may not be familiar with operating electronic equipment, it is likely that they may respond in an unexpected manner. For example, the patient may take a medicine bottle from the platform before prompted to do so, or replace a medicine container on section of the platform other than the scale-top pane. The software on our prototype is designed to handle these unexpected inputs and changes.

Every time the user interacts with a medicine bottle, its weight is recorded and saved as its "most recent weight." The next time that medicine is to be taken, its weight is compared to its most recent weight. If any medicine is missing, the caregiver is alerted. RMAIS can also recognize foreign bottles on the platform by comparing each bottle's RFID tag against a list of known medicines as it passes across the scale-top pane. If the medicine is not recognized, it is automatically added to the system. If a bottle's RFID tag is damaged or removed, the system also alerts to the patient.

III. EVALUATION

The functionality of the final prototype was tested in a lab environment and performed as expected. In addition to this qualitative evaluation, specific tests were performed to test the scale and RFID reader. The testing of these two components is essential because they are at the core of the system's functionality, and were not designed specifically for this system as the other custom components were.

A. Scale Test

The scale was tested in order to determine its reliability when measuring medicine displacements that occur when a patient takes medicines. The main focus is on the minimum medicine dosage that can reliably be measured. This is judged by measuring the scale's precision when integrated into the rest of the prototype.

The scale is advertised to be precise to 1 milligram. However, in a non-laboratory environment and roughly integrated into the prototype, precision has been decreased. This is because of instability caused by ceiling fans, air conditioning, the nearby electronic components, and vibrations from the interior cooling fan. To test the scale's precision, the fully assembled prototype was set in a test room, and programmed to sample a constant weight 100 successive times using the same average of stable readings as in the counting algorithm. The experiment was first done in a controlled environment (no air conditioning or fan), and then repeated in a more typical environment with the air conditioner and fan turned on. The results for the controlled environment are shown in Fig. 9, and the results for the typical environment in Fig. 10.

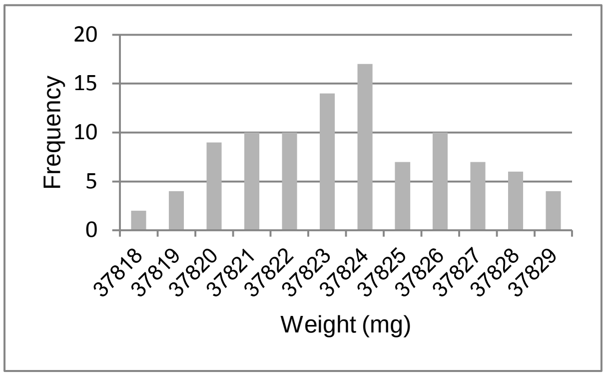


Fig. 9: Histogram of weight measurements in controlled environment.

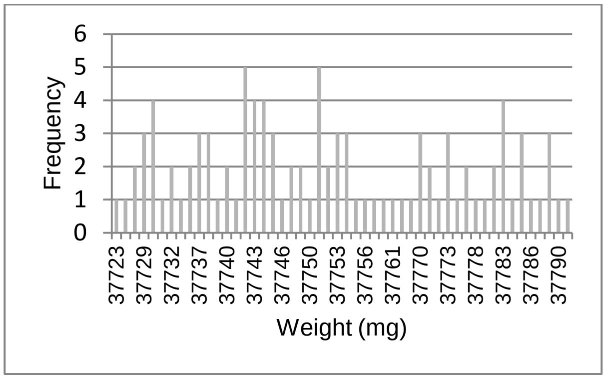


Fig. 10: Histogram of weight measurements in typical environment.

It is clear from the histograms that the controlled environment yielded much more stable results, with an actual imprecision range of 11 mg compared to 68 mg in the typical environment. From the range calculations, the theoretical minimum dosage weight is estimated to be 137 mg in a typical environment.

From the analysis above, we conclude that in the worst case, our current prototype can count pills or liquid dosages that are at least 137mg in size while maintaining 100% reliability (a very strict requirement). This high value of imprecision makes the system unusable for patients with smaller pills (such as Coreg or Ativan which have a weight on the order of 10 milligrams) or inhalers. When a commercial-grade RMAIS is put into production, the final design will be able to reduce this number by better integrating the scale into the device and including a partial cage around the weighing area to protect from the environmental conditions (further discussed in Section V.B). In addition, different accuracy of scales can be built into RMAIS systems to be used for different patients according to their needs.

TABLE 3: RESULTS OF THE PILL TEST

Condition	1 Pill	2 Pills	3 Pills	4 Pills	5 Pills
150mg (5 pills)	Pass	Pass	Pass	Pass	Pass
150mg (250 pills)	Pass	Pass	Pass	Pass	Pass
1500mg (5 pills)	Pass	Pass	Pass	Pass	Pass
1500mg (50 pills)	Pass	Pass	Pass	Pass	Pass

The scale was then tested in a realistic scenario (inside room with air conditioner and fan turned on) to ensure that it is able to detect the displacement of a number of pills. This was done by measuring the displacement of 1, 2, 3, 4, and 5 pills from an initial quantity of 5 and 250. This test was repeated for pills of 150mg each and 1500 mg each. For the large 1500 mg pills, the maximum initial quantity was lowered from 250 to 50 so that a reasonable sized container could be used. The test was 100% successful, which is expected being that 150 mg is above the previously calculated minimum. The results are shown in Table 3.

We tested medicine containers in both bottle format and box format. The results showed that the container format does not affect the system usage and operations, as long as the medicine container can be placed inside each compartment. The device's stationary platform (the round rotation surface shown in Fig. 4) can be made into arbitrary size to accommodate different sizes of medicine containers.

B. RFID Reader Test

The RFID reader was tested to ensure that it is able to detect a medicine container no matter where it is placed on the scale-top pane. This test was done by repeatedly reading the RFID reader's response as a medicine container was manually moved around the scale-top pane. The results show that the container could only be read if the edge of its RFID tag was within about 0.3 inches of the edge of the RFID reader. Because the RFID reader is attached to the bottom side of the scale-top pane, which was made from transparent polycarbonate plastic, a portion of the scale-top pane is unreadable due to the signal blockage by the plastic. To improve the peripheral range, the RFID reader should be moved downward in its mounting hole (to be closer to an RFID tag on the bottom of a medicine container on top of the scale-top pane), or a larger antenna should be used. Fig. 11 is a visual approximation of the unreadable area. Any tag that is completely enclosed in the shaded area cannot be effectively read.

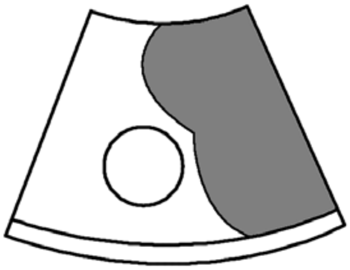


Fig. 11: A visual approximation of the unreadable area (the gray area) of the scale-top pane. The unreadable area can be reduced by using an RFID reader that has a larger reading range.

However, this unreadable area is not a major issue considering that the size of the RFID tags used are approximately the same size as the circle-shape RFID reader pictured in Fig. 12. If containers with a diameter larger than that of the RFID tag are used (such as the larger bottles pictured in Fig. 1) the edge of the centrally mounted tag is always within the functional (shaded) region. Additionally, the rotating spoke always rotates in counterclockwise direction and stops when it moves to the left edge of the scale-top pane, consistently positioning all containers in the functional region. In the case that the patient places a smaller container entirely within the nonfunctional (shaded) region, the device will time out and direct the user to adjust the container's position to the left half-part of the scale-top pane.

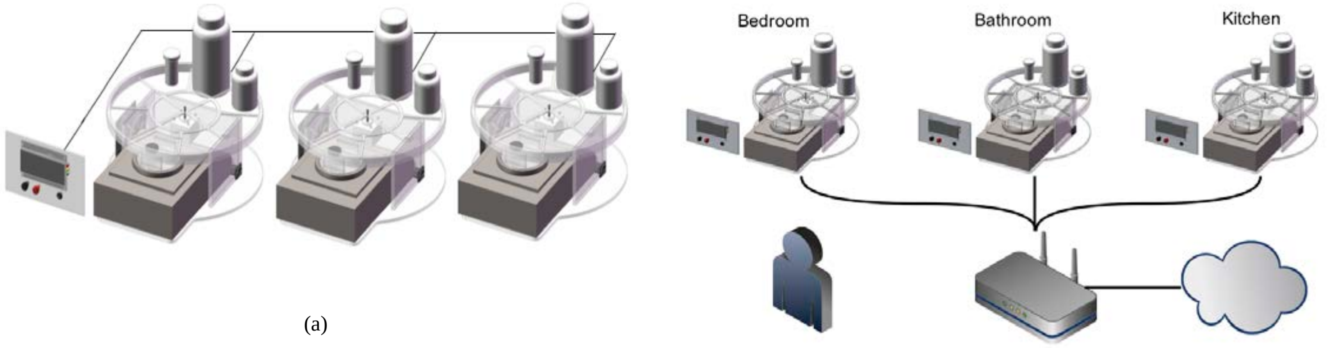
Furthermore, this short effective RFID reading range is actually a positive feature for the RMAIS system. It eliminates the potential risk of the RFID reader mistakenly reads a nearby medicine container's tag. In addition, as shown in Fig. 1 and Fig. 2, the RFID reader is also surrounded by two plastic walls that are used to connect the scale-top pane to the scale. Therefore, placing other RFID tags near the device does not create interference to the RFID reader, which was confirmed by our experiments.

IV. ADDITIONAL DESIGNS

A. Tandem Device Configuration

Our current RMAIS prototype works alone and can support up to 7 medicine containers as shown in Fig. 3. The number of supported containers can be arbitrarily increased by reducing the size of each section (for smaller medicine containers) or expanding the size of the top tray. In future work, we will further develop the system software to support multiple RMAIS devices in tandem for patients who have many medicines or who would like to take medicines in multiple locations.

Two forms of tandem configurations will be implemented as shown in Fig. 12. With such a design, the system can be easily and incrementally expanded to manage more medications than a single tray can hold, or to manage medications in separate rooms (or separate locations utilizing the Internet).



(a)

(b)

Fig. 12: Multiple RMAIS units can: (a) connect together to be placed in one location with a single user interface panel, or (b) connect to a home network. In this way, the patient can manage more medicines than a single tray can hold, or manage medicines in separate rooms.

If multiple family members in a household use RMAIS devices at the same time, each person should be assigned with her own RMAIS device unit or units. However, there is still a potential issue of one person erroneously takes medicines from the RMAIS device belonging to the other family member. There are various ways to eliminate or reduce such event. The simplest way is to stick a large name tag on the front side of each RMAIS unit. Another more enforced and technology-based way is to allow electronic authentication between each RMAIS unit and a patient. For example, a patient could wear a simple wristband with an integrated RFID tag. Whenever she wants to take medicine from a RMAIS unit, she places her wristband close to the RFID reader on the scale-top pane of the RMAIS unit. The RFID reader reads the tag information to decide whether the patient is authenticated to use this device.

B. Hardware Optimization

Our ultimate goal is to transform the RMAIS prototype into a production grade system that can be used with real patients. Moving towards this goal, we will optimize the hardware design in two ways.

First, the built-in RFID reader and scale can only track a medicine container that is on top of the scale-top pane. If a patient or her family members accidentally interact with a container on the other sections of the stationary platform, the device would not be aware and may introduce errors or false alarms until the tray is rechecked. Since all operations should deal with a medicine container on top of the scale-top pane, we will design a cage that partially surrounds the medicine platform in such a way that accidentally accessing the wrong container is prohibited or more difficult. The cage design is illustrated in Fig. 13.

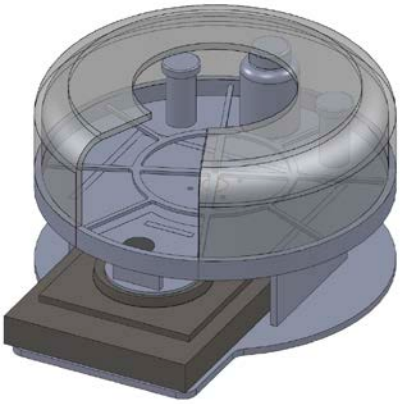


Fig. 13: The optimized version of RMAIS includes a top cage and an integrated scale that reduces the total height, weight, and cost of the device.

Second, in our current prototype we had to purchase a generic laboratory scale, which is large and expensive. We plan to build a customized and integrated scale that is much smaller than the generic scale by removing all unused functions and the display/control panel from a generic scale. Fig. 13 illustrates the outlook of RMAIS after these two hardware optimizations are completed.

V. CONCLUSION

In this paper, we presented a novel and practical medication self-management system. The novel features of the presented RMAIS system, such as the hardware interface designed for the scale, the spoke mechanism used to position medicine containers, and the software protocols used to interface the system with the pharmacy, provide a significant contribution to the research on in-home healthcare and medication self-management. The availability of the published prototype hardware and software components in [31] will also be valuable to researchers if a similar or subsequent system is developed.

The presented RMAIS system has broader impact to the development of the medical engineering field. The RFID usage is not the essential contribution for RMAIS. The real contribution is the design philosophy that we should make medical devices to be patient-friendly and can complete most operations in fully automatic ways. The RMAIS system implemented this design philosophy in the following three forms: the automatic medicine information input (via RFID tag and built-in reader), the automatic measuring of medicine dosage intake by a patient (using the scale), and the automatic rotating the correct medicine container to the front of a patient.

The next step for us is to implement the additional designs discussed in Section IV, and conduct a thorough clinical trial to study the real usability of the proposed system and discover additional problems for further improvement.

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Ethical approval: Not required

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