# A Robotic System for Autonomous Medication and Water Delivery

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***Abstract*— Poor medication adherence and dehydration are well-documented challenges for older adults living independently that lead to reduced quality of life. Robotic delivery of pills and water in the home could potentially improve medication adherence and hydration for older adults by providing timely, reliable, and convenient delivery. In this technical report, we present a prototype multi-robot system that can autonomously deliver pills and water to a person in a realistic home environment. The system consists of a mobile robot with a tray, a stationary dispensing robot, and a smartphone carried by the user. Within this paper, we discuss the opportunity to improve quality of life, describe our robotic system, and convey results from an experimental evaluation of the system's delivery performance.**

## I. INTRODUCTION

Medication plays an important role in healthcare as one grows older. People are more likely to develop one or more chronic illnesses with advancing age that require medication, and, in general, appropriate medication can help seniors live longer and more active lives. However, medication use in older adults is also more likely to be associated with safety concerns. Age-related challenges like memory loss can cause seniors to under dose or overdose. Poor eyesight can make it harder to read instructions or distinguish between pills. Physical ailments, such as arthritis, can make opening medication containers difficult [1]. Pills are typically supposed to be taken with water, and dehydration is itself a serious health risk for older adults due to a variety of factors, including a reduced sense of thirst [2].

A number of technological interventions have been proposed to assist older adults with these issues, including the use of electronic reminders, smart pill boxes that track and report usage, and stationary pill dispensers that release medicine at appropriate times [3]. Unlike these interventions, robots have the potential to emulate the ability of a human caregiver to physically deliver medicine and water to an older adult. Physical delivery eliminates the need for the older adult to interrupt his or her activities in order to go to the medicine, prepare the medicine, go to a source of water, and prepare a drink of water. As such, when compared to other technological interventions, we would expect the robot to lower both the physical and mental workload associated with taking medicine and drinking water and thereby improve medication adherence and hydration [4].

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(a) (b)

Fig. 1: Current delivery system a) mobile robot b) autonomous medication station.

### A. Two Challenges for Autonomous Delivery

Within this paper, we focus on the problem of delivering pills and water to a person in a realistic home environment. This entails two main technical challenges. First, the robot needs to acquire and prepare the pills and water. Second, the robot needs to locate and move next to the user with the pills and water.

To address the first challenge, we have developed a stationary dispensing robot that prepares and places the pills and a cup of water on a mobile delivery robot's tray. In essence, this stationary robot performs the manipulation required for the task (see Figure 1). Prior to dispensing, the delivery robot must dock with the dispensing robot. To do so, it first performs coarse navigation by using a labeled map to move to the vicinity of the dispensing robot. It then performs local navigation via a beacon to dock with the dispensing robot.

To address the second challenge, we have developed a smartphone interface and a gesture-based interface. Through a smartphone carried by the user, the robot alerts the user that it wishes to deliver pills and water, and asks for the user's location. The user then provides the name of the room he or she is in via speech. The robot uses this room name and a labeled map of the home to perform coarse navigation into the room. Once in the room, the robot looks for a gesture to identify the intended recipient and estimate his or her 3D location. The robot then uses this 3D location for local navigation up to the recipient.

Together, the delivery robot, dispensing robot, and smartphone comprise a complete robotic system capable of autonomously delivering pills and water to a person in a realistic home environment. For the rest of this paper, we provide additional motivation for this form of robotic assistance (Section II), discuss related research (Section III), describe the details of our robotic system (Section IV), and present our experimental evaluation of the system's delivery performance (Sections V and VI).

## II. Motivation

Seniors are the largest consumers of all types of medication in the United States. The Centers for Disease Control and Prevention (CDC) states that while seniors make up only 15% of the U.S. population, they account for nearly one-third of drug prescriptions. Seniors are also more likely to accidentally overdose on medication because of forgetfulness. The United States spends $290 billion annually on the management of medication-related problems [5]. Older adults are disproportionately affected by the possible toxic consequences of medication. A 2005 study published in Pharmacotherapy revealed that over two-thirds of hospitalized older adults had an adverse drug effect over a four-year period [6]. The outcomes of these occurrences included functional declines that resulted in nursing home placement.

Several solutions have attempted to address these problems. Increasing the print size of medication labels can help to alleviate issues with reading dosage instructions. However, it does not alleviate difficulties with differentiating between individual pills. Computerized pill dispensers can remove the need for opening medication containers (if prefilled by a caregiver) and assist in reminding seniors when to take their medicine by utilizing alarms. Nevertheless, the senior must still make an effort to retrieve the pill from the dispenser and pour a cup of water. As a result of these additional steps, seniors also run the risk of silencing the alarm intending to remind them to take the pills, but neglecting to return. Employing in-home help (human assistant) can lessen the feeling of loneliness felt by seniors that live alone and assist them in complying with their medication schedule. Unfortunately this option is not cost-effective for many families. In 2011, the average cost for a home health aide in the U.S. was $20 per hour [7].

## III. Related Work

As it relates to robotic research in this area, [8] describes a European FP7 project called "CompanionAble", which is a socially assistive home robot companion for older adults with mild cognitive impairment that live alone. The goal of this project is to allow these adults to remain in their home for as long as possible by utilizing assistive technologies. The mobility of this system has proven to be one of the main benefits because it simplifies interactions and allows for a multitude of possible assistive functions. These functions include greeting the user upon returning home, initiating video calls with family or caregivers, or detecting falls within the home. One of the main capabilities of the system also includes intelligent reminding (i.e. for taking medicine or drinking water). The deployment of a service robot to help older people involved the deployment of a mobile service robot in an independent living facility for over two months, which included the participation of 32 residents and 21 staff [9]. It demonstrated that assistive care robots can successfully interact with people and become accepted. The service robot was equipped with many functional modules including a periodic hydration reminder. Additionally, an assistive robot that uses human-like gestures to determine affective state in order to better interact with the user was examined as a method for influencing the outcome of reminders to complete tasks, such as taking medicine, eating, and going for a walk [10].

An intelligent medicine case, iMec, has been developed that uses computational models, a network of embedded sensors, and a database server to determine if an older adult has picked up the correct medicine from its storage space [11]. The system also attempts to estimate if the dose is taken at the right time. This information is linked to an external database for access by designated caregivers. A wearable notification display for supporting medication adherence is presented with the goal of enabling older adults to keep up with their medication by providing additional information to ease the process[12]. This information includes reminding, coaching, and persuading.

The systems described above utilize various methods to either monitor, remind, or persuade the user to take their medication and drink water to stay hydrated. What they do not do is reduce the physical load of the user by physically delivering the proper medication and hydration to the user within his or her home. This is an important motivation for our research.

As far as delivery robots, [13] describes a wheelchair-mounted robotic arm (WMRA) with an attached tray where the arm places retrieved objects. The tray is within arms reach of the user, so objects are easily retrieved. However, WMRAs require that the user drives the wheelchair system to the desired object in order for the arm to grasp it. This could add an additional cognitive and physical load on the user and requires them to navigate to the location of the desired object. Our system provides automatic delivery and only requires the user to verbally indicate his or her location.

One recent work that has gained publicity is the PR2 and Turtlebot team that works together to deliver drinks retrieved from a refrigerator [26]. While the Turtlebot travels to a location near the refrigerator, the PR2 takes the drink, requested wirelessly from a human, out of the refrigerator. Once the Turtlebot arrives, the PR2 places the drink on top of a tray attached to the Turtlebot. The Turtlebot then travels to the room where the human that requested the drink is located. This approach utilizes the more expensive PR2 system to achieve delivery, while our method employs a more affordable and less complex system.

Mobile robots have been developed that help deliver items to older adults and individuals with motor impairments. EL-E is a behavior based mobile manipulator capable of delivering an object to a motor-impaired user [14]. Their research involved user studies with 7 patients with amyotrophic lateral sclerosis (ALS) and 1 patient with primary lateral sclerosis (PLS) to determine if the users preferred a robot to hand items to them or alternatively, to place them on a nearby table. The target population of this work is closely related to the user group that would potentially utilize our system and is motivation for our work. Mobile Assistant Robot for You (MARY) [15] and Care-O-bot 3 [16] are mobile manipulators that retrieve and deliver objects by placing them on an attached tray, before navigating to the user. In addition, CERO [17] delivered objects that have been placed on top of it to a motor-impaired individual. These systems either require a robotic arm to manipulate an object or require a human to place an object on a tray attached to the robot. The need for an additional human in the loop for placing an object on the robot's tray reduces operating capabilities and the usefulness of a system. Our work utilizes a low cost multi-robot system to provide medication and water delivery without the need for an additional human in the loop or a robotic manipulator.

The navigation capabilities of these projects are made possible by prior research in hybrid navigation architectures [18], Monte Carlo localization [19], and path and motion planning [20] [21] [22] [23]. We recognize these works as building blocks for today's mobile robot systems.

## IV. System Design

### A. Mobile Robot

The mobile portion of our robotic system consists of an augmented Willow Garage Turtlebot robot. The Turtlebot is a low-cost, personal robot consisting of open-source hardware and software. The open-source software that controls the robot consists of the Robot Operating System (ROS), which provides libraries and tools for creating robotic applications. The main components of the Turtlebot are a Microsoft Kinect sensor (for visualization of the world in 3D), a netbook, and an iRobot Create robotic base. The main Kinect sensor is used for navigation within a known environment. We modified the standard Turtlebot with an additional Kinect sensor. This sensor is used to enable gesture recognition for identifying the position of the target user.

### B. Medication Station

We constructed a prototype of the robotic medication station to enable automatic medication and water dispensing. The station consists of a cup dispenser, medical pill dispenser, water dispensing unit, servo motors, and a netbook. We augmented the standard dispensers with mechanical actuators to enable autonomous control. These actuators are controlled by a software program running on the netbook, which is activated by the mobile robot through a wireless network connection. The mechanical actuators consists of three Robotis Dynamixel robot servos and each servo actuates one of the dispensers. The dispensers include an Accutab pill dispenser, a push button water cooler cup dispenser, and a water spigot attached to plastic tubing for providing water. We mounted the actuators and dispensers on an Azar pegboard in order to provide a base for the medication station. We enable the robot docking capabilities by utilizing the standard Roomba charging station. It provides a infrared signal that guides the robot to an appropriate position for receiving items for the dispensers. The details of the medication station are illustrated in Figure 2 .

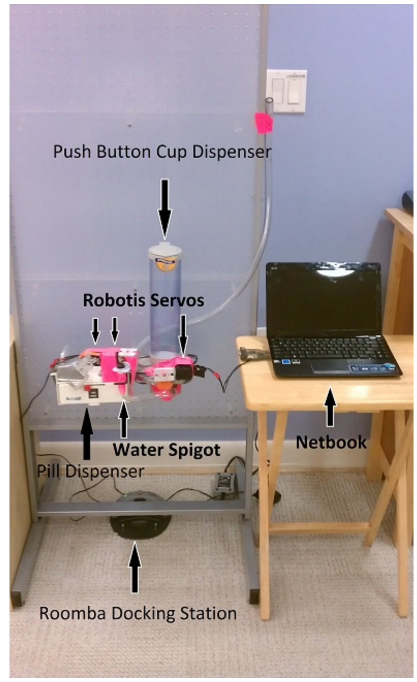



Fig. 2: Composition of the medication station.

### C. Human/Robot Communication Channel

A critical problem addressed by our research relates to how the robot will locate a user within the home. Our solution leverages the widespread use of smart phones in today's society. Numbers vary, but as many as 15% of people aged 55 and older are using smartphones, according to data from Nielsen [24]. The prevalence of smart phone use by older adults is likely to increase over time. Moreover, people typically have their smartphones located near them, even when in the home. There are many existing medically related smartphone applications that are intended to benefit seniors (i.e. Guardly, Tell Me Geo, Personal Caregiver, Pain Care, iBioMed, Public Speech).

We have designed an Android application that allows the robot to communicate with the user. The application allows the robot to ask for the user's location and use his or her response to determine the navigation goal of the robot. The Android application interface is illustrated in Figure 3. For example, if it is time for the senior to take his or her medication, then the robot can use the smartphone to generate verbal statements such as "Where are you in the house? The senior then verbalizes his or her location into the smartphone. Standard Android-based natural language software on the phone translates the user speech into an actionable goal location for the robot. For example, the senior could say I am in the living room. Prior to going to the living room, the robot navigates to the medication station to collect medication and water. Once it arrives at the medication station, it wirelessly communicates with the station and instructs it to dispense a cup, to fill the cup with water, and to then dispense the scheduled pills into its built-in tray. Once retrieved, the robot moves to the room that the senior indicated via the smartphone. After arriving in the room, the robot must now locate the user within the room.

As part of the system, we have developed a gesture recognition system that recognizes a raised hand, calculates the coordinates to the raised hand, and uses these coordinates to navigate the robot closer to the user. The gesture recognition system is developed using Microsoft's official Kinect SDK and .NET technology. It uses skeletal tracking to identify the user. If the user raises his or her hand, then the coordinates of the hand's location are used to calculate the approximate location of the user. The raised hand is recognized when the x-coordinate (height) of the skeletal representation of the user's hand is greater than the x-coordinate of the skeletal representation of the user's head. The robot uses this location to navigate closer to the user.

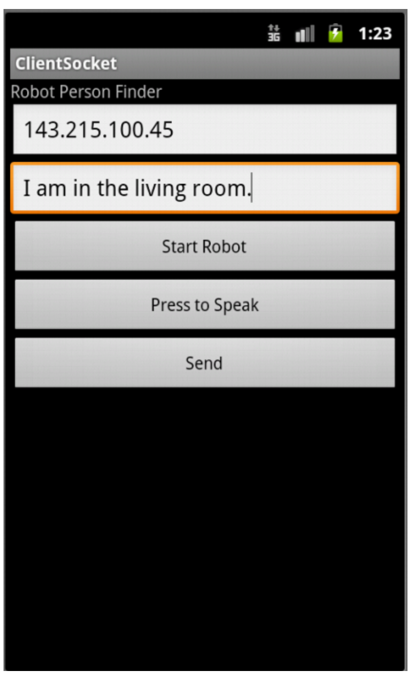



Fig. 3: Android application user interface. The top textbox is designated for entering the local IP address of the robot. The next textbox captures the spoken commands of the user. The "Start Robot" button initiates the system. The "Press to Speak" button initiates the speech recognition functionality. The "Send" button sends the spoken commands to the robot.

## V. Experimental Design

### A. Approach

We tested the robustness and reliability of our medication and hydration delivery system through a series of experiments. We recruited a non-student volunteer to participate in 20 experiments. Our goal was to determine how well the system can query a user's location, retrieve the delivery items, and successful delivery it to the user. For experimental purposes, the delivery items were Tic Tacs and water.

We conducted the experiments on the first floor of the Georgia Tech Aware Home [25]. The Georgia Tech Aware Home is a 3-story, 5040 square foot home which provides an authentic research facility designed to facilitate research related to the introduction of technology in a home setting.

Prior to running the experiments, we constructed a map of the first floor of the Aware Home by driving the robot around and using its sensors to build a 2D representation of the environment. The constructed map is shown in Figure 4. We then annotated the coordinate locations of the kitchen, living room, and the medication station within the map. These coordinates were used as waypoints for the robot to utilize when traveling to different portions of the house. In order to find the location of the user within the room in which she was located, we designed the robot to detect when a person raises his or her right hand. This location of the user's hand is identified by the robot and used to determine a new approximate navigation goal (Figure 5d).

Fig. 4: Robot generated map of the first floor of the Georgia Tech Aware Home.

An example interaction is illustrated below (also see Figure 5):

1) The interaction begins when the robot queries the user's smartphone asking which room the user is located in (e.g. kitchen, living room, bedroom).
2) The user indicates his or her location via voice.
3) The robot travels to the medication dispensing station, avoiding obstacles, and instructs the dispensing station

to dispense a cup, fill it with water, and to then dispense the medication (we used Tic Tacs for this experiment).

4) Once it has obtained the medication and water from the station, the robot continues to the location indicated by the user.
5) The robot reaches the location and begins to incrementally rotate at a constant angular velocity while it looks for a person with a raised right hand.
6) The targeted user raises his or her right hand.
7) The robot recognizes the person with the raised hand and navigates to a location near the person.

### B. Design

We tested our system on the first floor of the Aware Home. The Aware Home's first floor consists of a living room, a kitchen, several bedrooms, a hallway, and a bathroom. The delivery experiments were conducted with the user located in either the kitchen or the living room. These two locations were chosen because they represent different delivery environments and because experiments conducted by other researchers were being run in the bedrooms and bathroom. The living room is large and carpeted and gives the system a consistent and level plane for navigation. The kitchen's floor consists of hardwood, with an area rug under the kitchen table. Navigating in this area, the system encounters a transition from carpet to hardwood flooring as it moves from the hallway into the kitchen.

We conducted a total of 20 trials with one volunteer as the target user. We conducted 10 trials in the living room and 10 trials in the kitchen. Five different locations in each room were marked with tape in order for the experimenter to take measurements and two trials were run at each location. Figure 6 shows the living room and kitchen with the designated locations marked with pink tape.

(a) (b)

Fig. 6: The designated locations for the user are marked with pink tape in the a) living room and the b) kitchen.

We have identified seven potential failure points that could impact the ability of the system to deliver over the course of the experiment. These failure points were determined by examining the points of failure during system development. The type of failure (F1 - F7) is segmented by where the failure occurs. The failure types include:

F1. The robot does not respond to user's indication of location.
F2. The robot does not dock with the medication station.
F3. The medication station does not properly dispense items.
F4. The robot does not undock from the medication station.
F5. The robot does not navigate to the location of the user.
F6. The cup of water tips over while the robot navigates to the user's location.
F7. The robot does not recognize the user's gesture and does not navigate to her.

If the robot successfully locates the user and delivers the items, then the final distance from the robot to the marked location of the user was measured and recorded. If a failure point is encountered before delivery is achieved, then that specific failure was recorded.

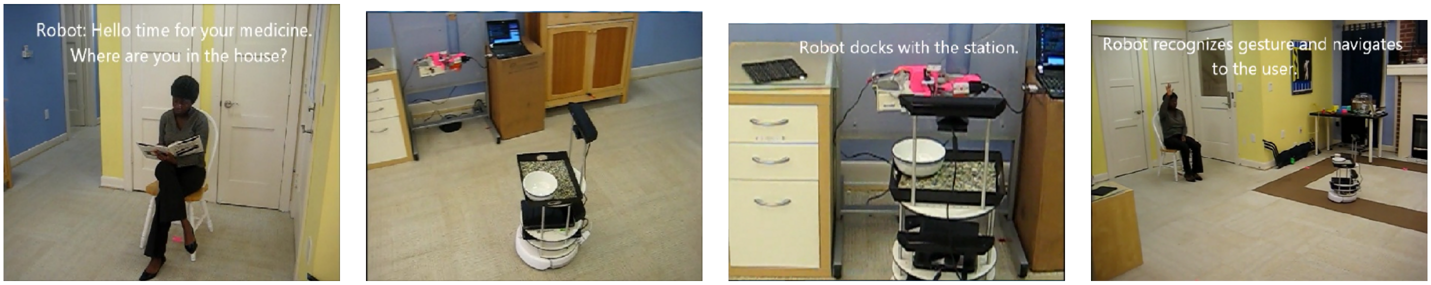
## VI. Results

The results of the 10 trials conducted in the living room of the Aware Home are listed in Table 1. The system failed during trial 2 and trial 5. During trial 2 the robot successfully responded to the user's indication of her location through the smartphone, but did not properly dock with the medication station while attempting to retrieve the delivery items. During trial 5, the robot successful responded to the user's indication of her location, docked with the medication station, instructed the station to dispense the items, undocked, and navigated to the user's location. However, the robot did not recognize the user's gesture (raising of her right hand) in order to locate her exact position. The other eight trials were successful and averaged a delivery distance from the user of 95.3 cm, ranging from 92.7 cm to 99.7 cm.

| **Location: Living room** | **F1** | **F2** | **F3** | **F4** | **F5** | **F6** | **F7** | **Delivery Distance (cm)** |
|---|---|---|---|---|---|---|---|---|
| **Trial 1** | | | | | | | | 95.3 |
| **Trial 2** | | X | | | | | | N/A |
| **Trial 3** | | | | | | | | 99.7 |
| **Trial 4** | | | | | | | | 94.0 |
| **Trial 5** | | | | | | | X | N/A |
| **Trial 6** | | | | | | | | 92.7 |
| **Trial 7** | | | | | | | | 95.3 |
| **Trial 8** | | | | | | | | 94.0 |
| **Trial 9** | | | | | | | | 97.2 |
| **Trial 10** | | | | | | | | 94.6 |

TABLE I: Living Room Delivery Success/Failure Matrix

The results of the 10 trials conducted in the kitchen are listed in Table II. Failed deliveries occurred during trial 1, 3, 5, 6, and 8. During trial 1, 5, and 8 the cup tipped over spilling the water while the robot traveled to the location of the user. In each instance the cup of water tipped over while the robot traversed from the carpet in the living room to the hardwood floor and area rug in the kitchen. There is a point where the floor changes from carpet to hardwood floors back to the carpet of the area rug in the kitchen (Figure 7). The cup of water tipped over in each instance during these abrupt




(a) (b) (c) (d)

Fig. 5: a) User indicates her location through the smartphone. b) Robot navigates to the medication station. c) Robot docks and instruct the station to dispense a cup, fill it with water, and dispense the Tic Tacs. d) Robot locates user through gesture recognition and navigates to her.

Fig. 7: Transition from carpeted living room to kitchen with hardwood floors.

| **Location: Kitchen** | **F1** | **F2** | **F3** | **F4** | **F5** | **F6** | **F7** | **Delivery Distance (cm)** |
|---|---|---|---|---|---|---|---|---|
| **Trial 1** | | | | | | X | | N/A |
| **Trial 2** | | | | | | | | 97.8 |
| **Trial 3** | | | | | | | X | N/A |
| **Trial 4** | | | | | | | | 95.9 |
| **Trial 5** | | | | | | X | | N/A |
| **Trial 6** | | | X | | | | | N/A |
| **Trial 7** | | | | | | | | 96.5 |
| **Trial 8** | | | | | | X | | N/A |
| **Trial 9** | | | | | | | | 98.4 |
| **Trial 10** | | | | | | | | 99.7 |

TABLE II: Kitchen Delivery Success/Failure Matrix

transitions. During trial 3, the robot delivered the items to the location of the user, but could not recognize the user's raised hand in order to identify her exact location. During trial 6, the robot navigated to the medication station, but the station did not properly dispense the delivery items. The other five successful trials averaged a delivery distance from the user of 97.7 cm, ranging from 95.9 cm to 99.7 cm.

## VII. Discussion

The system successfully delivered items to the user 8 out of 10 times when the user was located in the living room. The two failures occurred when the robot attempted to dock with the medication station and when the robot did not recognize the user raising her hand to indicate her exact position. These failures were attributed to software malfunctions that occurred during the docking and gesture recognition process. We expect that our future work will solve this problem by including methods for error recovery that will allow the robot to retry certain actions if it encounters a failure point.

The system performed 5 out of 10 successful deliveries when the user was located in the kitchen. Three of the five failures occurred when the robot tipped the cup of water over while it navigated to the location of the user. These errors occurred while the robot transitioned from carpet to hardwood and then back to carpet (see Figure 7). This uneven terrain caused enough jarring of the robot to tip the cup of water over. The addition of a specialized cup holder could help to alleviate this problem by preventing the cup from tipping while the robot traverses over uneven terrain. During one of the trials the medication station did not properly dispense the cup to the docked robot because the cup was stuck in the dispenser. We plan to improve the mechanical design of the dispensers in order to rectify these types of issue and increase the overall robustness of the system.

## VIII. Conclusion and Future Work

This paper describes a multi-robot system designed to provide automatic medication and hydration delivery to a user within his or her home. The system consists of a small mobile robot, an autonomous medication station, and a smartphone-based communication application. The robot verbally queries the location of the user through his or her smartphone and then navigates to the medication station. Once it arrives it instructs the station to dispense a cup, fill it with water, and then dispense the medication (Tic Tacs in these experiments). The robot undocks and travels to the location indicated by the user (e.g. living room, kitchen). The robot then slowly spins in a circle and attempts to find the user's location by detecting his or her raised hand. Once detected, the robot navigates to a position closer to the user.

We ran experimental trials with the user located in the living room and the kitchen. The results of the trials were promising, but also revealed areas that need improvement in the design and robustness of the system. Future work will focus on improving the robustness of the system both through enhanced software and improvements in mechanical design.

Some of the obvious limitations of the multi-robot system include the fact that it can only operate in one level living environments (it cannot go up or down stairs). Also, its navigation and localization may be better in smaller environments ( less than 1500 sq ft) as opposed to larger environment. However, the target population usually dwell in apartment style living arrangements that are well suited for our solution.

We also expect that additional system capabilities might be advantageous. Currently, the robot must look around slowly in order to detect the person's gesture, and the gesture must be timed to occur when the robot is looking. In future versions of the system, we anticipate both more rapid scanning of the environment by the robot, and autonomous methods to detect people. Once a person is detected, the robot could potentially ask for the person to give a gesture as confirmation. Furthermore, if the user chooses not to immediately take the medicine and water upon delivery, the robot could wait as a physical reminder, or potentially follow the user, until the user either takes the medicine or sends the robot away to return later. The robot might also integrate awareness of the user's activities or adapt over time to find more effective times for delivery. For instance, a pill may need to be taken with food, and an older adult may eat a different times of the day. More generally, this type of multi-robot system could deliver other items that would benefit older adults. For example, a blood pressure cuff or thermometer might be delivered to improve health monitoring.

Our first priority, however, is to use our prototype system to perform human-robot interaction studies with older adults in order to better understand their needs. In the longer term, we hope to conduct long-term studies in natural settings.

The experiments we conducted in this paper with our multirobot system are a necessary precursor to more elaborate human-robot interaction. The motivation of our work is to develop a system that can improve the medication adherence and hydration of older adults with a low cost multi-robot system that does not use an on-board general-purpose manipulator. A low cost system of this nature can potentially accelerate the use of robots in home healthcare settings.

## IX. ACKNOWLEDGMENTS

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