An Adaptive Software Framework for Dementia-care Robots

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Abstract

Ample amount of research has been done on designing robot hardware and software to care for individuals with Alzheimer's dementia (IAD). A major issue of the software frameworks for dementia-care robots is the lack of adaptivity: every change in the care protocol (i.e. high-level activity planning for the robot) needs to be manually accommodated in the software by a robotics expert. We propose an alternative approach for designing software framework for dementia-care robots which will allow lay users (i.e. caregivers of IAD) to change the care protocol in a seamless manner. This is achieved through employing domain independent AI planning along with planning domain definition language (PDDL) to define a high-level planner for the robot that implements the care protocol. A caregiver can customize a default care-protocol at any time through answering a set of simple questions which automatically updates the PDDL file and, in-turn, the planner. We used this novel approach to design two dementia-care protocols and implemented it on a robot. The robot performs planning based on information from commercially available smart-home (SH) sensors that detects activities related to the care-protocol. We evaluated the adaptivity of this framework through a user study where caregivers of eight IADs re-designed the care protocol according to their needs. To the best of our knowledge, we are the first to leverage PDDL and domain independent AI planing to design adaptive software for dementia-care robots.

Introduction

Inspired by the demographic shift of world population, the prevalence of Alzheimer's dementia among elderly, and the high cost of dementia-care, a large body of research has been dedicated to design Socially Assistive Robots (SARs) that can support individuals with Alzheimer's dementia (IAD) to age-in-place through assisting in their daily activities. Research in this direction can be categorized into two groups: i) investigation of human factors, such as utility, acceptance, and usability, involved with having a robot in the role of a carer through carefully designed human-robot interaction (HRI) studies (Mordoch et al. 2013; Bemelmans et al. 2012; Broekens et al. 2009; Kachouie et al. 2014; Moyle et al. 2014; Begum et al. 2015; 2013; Chu et al. 2017) and ii) design of robot, sensors and software to make SAR -based dementia-care a reality (Wu, Fassert, and Rigaud 2012; Cavallo et al. 2013; Gross et al. 2019). This paper belongs to the second group and focus on adaptive software development to facilitate SAR-based dementia care.

Designing intelligent software framework to realize SAR-based dementia-care is an active research trend. The works reported in (Boger et al. 2005; Grzes et al. 2014; Hoey et al. 2011; 2014) iteratively developed a Partially Observable Markov Decision Process (POMDP)-based decision-making framework to provide step-by-step guidance to IAD in their activities of daily living. Similarly, the works in (Schroeter et al. 2013; Jayawardena et al. 2010; Huijnen et al. 2011; d IRCCS 2017; Fischinger et al. 2016; Bajones et al. 2018) designed robots and supporting software framework for dementia-care. From an algorithmic perspective, a commonality among these works is they designed software to execute a set of pre-defined tasks by the robot in a known sequence. In other words, the robot executes pre-coded high-level plans (e.g. moving to a certain place to deliver a certain object when a certain event is detected in the environment) while exercising some level of autonomy in low-level planning (e.g. how to safely move from one place to the other). If the high-level plan changes, none of the existing frameworks can adapt to that autonomously. Instead, a robotics expert will have to manually incorporate those changes, e.g. through redesigning a POMDP or adding different functionalities to the existing software framework. This is a major gap in the contemporary research on robot-based dementia-care. This paper attempts to bridge this gap through proposing the use of domain independent AI planning along with planning domain definition language (PDDL) to define the care-protocol for dementia-care robots. PDDL, a tool that facilitates the use of domain-independent AI planners for a multitude of planning problems (Edelkamp and Hoffmann 2004), is increasingly gaining popularity among the AI community because of the recent support through ROS-Plan package (Cashmore et al. 2015; Quigley et al. 2009). Despite their strength, the use of PDDL and ROSPlan have so far been limited to problems in simulation (Cashmore et al. 2014; 2017) or extremely simplistic real HRI problems (Sanelli et al. 2017). To the best of our knowledge, we report the first effort in adapting this powerful set of planning tools for a complex HRI problem such as dementia-care. We propose to use simple interfaces for knowledge engineer-

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ing (KE) that can enable lay users to customize the high-level plans of a SAR through automatic generation of PDDL files. To evaluate the proposed approach we designed a SAR to implement two dementia-care protocols. The robot uses a set of commercially available IoT devices to detect activities related to the care-protocol in order to make high-level plans for executing these protocols. We evaluated the adaptivity of this framework along with its technical feasibility through a user study where familial caregivers of eight IADs re-designed the care protocol according to their needs through a simple interface.

The two main contributions of this paper are:

- design and implementation of a software framework for a dementia-care robot using domain-independent AI planning, and
- a knowledge-engineering technique to accommodate lay-users' choices/preferences in the domain independent AI planner in a seamless manner and evaluating it through a user study with caregivers of IAD.

The rest of the paper is organized as follows: Section 2 provides a brief background on the use of PDDL and KE for robot planning. Section 3 discusses the two care-protocols that we implemented using the proposed adaptive software framework. This section also discusses the SARhardware, IoT devices used by the SAR, and some measures observed to ensure software security. Section 4 describes the proposed KE-enchanced PDDL framework to implement the two care-protocols described in Section 3. Section 5 reports the user study and finally, Section 6 indicates some future directions of research before concluding the paper.

Background

AI Planning for HRI

Interactions between humans and robots in realistic problems often consist of different atomic actions. If the interplay among these atomic actions are well-defined, it is possible to use AI planners to generate a plan that will execute different atomic actions in such an order that fulfills the goal of the interaction. Domain independent AI planning can be used to make plans for any arbitrary interaction between humans and robots given that the planning problem is modeled in PDDL (Edelkamp and Hoffmann 2004). The recent support of the ROSPlan package (Cashmore et al. 2015) has made domain independent planning achieved through PDDL very popular among the AI community (Cashmore et al. 2014; 2017; Palomeras et al. 2016; Brafman, Bar-Sinai, and Ashkenazi 2016). The ROSPlan package offers developers a set of state-of-the-art domain independent planners (such as FF, POPF), including conditional planners (Hoffmann and Brafman 2005) that are crucial for realistic HRI applications, along with a framework to define the planning problem through PDDL. The work in Sanelli et al. (2017) leveraged ROSPlan to resolve a one-step planning problem namely, whether to interact or not, in the context of HRI. Petrick and Foster (2016) applied PDDL-based task planning in a more complex HRI system of a bartender robot, which involves multi-human interaction. The use of domain independent planning in complex realistic HRI scenario is largely restricted by the difficulty in defining the PDDL files. Extensive expertise in programming and AI is required to define PDDL files. In this paper, we propose to apply knowledge engineering techniques to autonomously build PDDL files that can cause AI planners to generate plans that are customized according to lay users' requirements.

Knowledge Engineering

Knowledge engineering (KE), by itself, is not a new domain in AI, machine learning and robotics. KE provides lay users with a way to make the underlying algorithm of an AI system aware of their preferences/choices. The only work that introduced KE in the software framework for dementia-care robots is reported in (Grzes et al. 2014). In this case, the robot used a POMDP-based decision making module to implement different care-protocols. The work in (Grzes et al. 2014) designed a KE technique namely, SyNdetic Assistance Process (SNAP), to allow the lay users to translate their knowledge into a customized POMDP model. The translation process is automated by encoding a probabilistic relational model into a relational database. This database is approachable by any lay user who is not an expert in POMDP. Although POMDP can model the domain uncertainty and compute a policy (i.e. a plan), the resultant policy is highly sensitive to system dynamics that are very difficult and time-consuming to determine with learning approaches. In addition to that, POMDPs are hard to explain to lay users which makes the caregivers unaware of how their choices are influencing the decision making process of the robot. In this paper, we propose an alternative approach where the decision making process of the dementia-care robot is based on conditional AI planning which is a more natural way to model online knowledge acquisition during human-robot interactions. In this approach, PDDL files used by AI planners can easily be translated to human readable descriptions that are understandable by lay users. To make our system usable to the lay users, we designed a KE procedure to let lay users translate their knowledge into a PDDL domain file.

A SAR for Dementia-care: System Overview

Care-protocols

Our team consists of clinicians (the 4th author of the paper) who works on age-in-place. The care giving needs of people with dementia, identified through our previous research and existing literature survey, inspired us to work on two highly common care-giving use-cases namely, medication reminder and prevention of wandering around (Ferrara et al. 2008; Rialle et al. 2008; Barnard-Brak, Richman, and Owen 2018; Collins 2018). we designed a SAR that can autonomously take care of these two care-giving needs according to a user-defined protocol.

Medication reminder Under this protocol the robot is expected to remind the IAD to take a certain medication at a particular time of the day. If the IAD does not respond to this reminder, the robot is expected to call and notify the caregiver. A caregiver can customize this baseline protocol to suit the needs of the IAD s/he is caring for through our proposed approach.

Preventing from wandering around Under this protocol the robot is expected to prevent the IAD from going out of the house at an unusual time, e.g. after 9 pm, through requesting him not to step out of the door at night. If the IAD does not respond to this request, the robot is expected to show a pre-recorded video of the caregiver making the same request. If this second level of reminder does not work, the robot is expected to call and notify the caregiver and an emergency personnel (e.g. the police). A caregiver can customize this baseline protocol to suit the needs of the IAD s/he is caring for through our proposed approach.

The SAR platform

We used a pioneer 3DX (figure 1(a)) as the SAR platform for dementia-care. The discussion on whether such a platform is suitable as a dementia care robot (e.g. due to lack of anthropomorphism) is beyond the scope of this paper due to its focus on the design of a novel AI planning framework for dementia care. A laptop is attached with the robot for all high-end computations. Figure 1(b) shows the ROS-based software framework we designed to deliver the two care-protocols. We organize all the software components in a layered system architecture as introduced in Gross et al. (2009). There are four layers in this framework and our main contribution lies at the planner layer.

Planner Layer This is the command center of the robot. It includes the executive and the AI planner. The executive connects and synchronizes all sensor information, generate a planning problem on the fly, call the AI planner with problem instance, and dispatch the plan. The AI planner includes several ROSPlan nodes that perform task planning. The planner reads a domain description file and a problem instance file, generates a plan which is a sequence of tasks. The details of the AI planner is discussed later in Section 4.

Task Layer This layer implements all tasks that the robot can accomplish. These tasks are available for the AI planner to generate the plan. The tasks are more complex control logic that make use of the robot's basic functions implemented in the "Skill layer". For example, the search and approach person task is implemented based on both auto-navigation skill and face detection and recognition skill. Whenever this task is included in the plan and dispatched by the executive, the robot will navigate itself to a sequence of pre-defined landmarks in the house and rotate itself to look for a human face. Once it detects a human face it will drive toward that face and try to recognize the face by matching it to the pre-defined face of the IAD. Similarly, in the phone call task, the robot will call an emergency number (e.g. a family member, police station, hospital or fire service) and describe the emergency. For this we implement a ROS node based on Twillow service [1]. In the remote control task, the robot is able to establish real-time video stream (Skype[2] is used in our implementation) that enables the caregivers to monitor and communicate with the IAD. In this implementation, the robot offers three types of access to a user (e.g. a caregiver, an emergency personnel): ***read*** where the user can see the information collected/processed by the SAR from around the house, ***write*** where the user can override the behavior of the SAR through changing different parameter of the software, especially the planning domain file which we will discuss in Section 4, and ***drive*** where the user can control the robot remotely and drive it to different places in the house while communicating with the IAD through a video stream. In the sensor monitor task, the robot reads the latest data of the IoT devices. These data are translated into state variables. In the notify message task, the robot will perform relevant communication skills such as play audio or video.

Skill Layer This layer hosts all basic algorithms for navigation, face recognition, speech recognition, localization, etc. We implemented this layer by integrating several state-of-the-art robotics algorithms available in various ROS packages, e.g. move_base [3], gmapping [4], *face_detector* [5], *face_recognition* python library [6], amcl[7]. To implement the communication skill, we build a script-running ROS node to play pre-defined audio and pre-recorded video.

Hardware Layer This layer hosts all hardware used by the robot, e.g. laser range finder, wheel encoder, camera, and IoTdevices.

Smart Home and IoT Devices

The robot uses two commercially available IoT devices to detect events in the environment related to the two care-protocol. Data from the IoT devices are processed in a local server before being transmitted to the robot. The IoT component of this project is implemented using Samsung SmartThings ecosystem[8], which provides a comprehensive framework for smart home and IoT devices. We implemented the project workflow and integrated it with SmartThings Cloud, IoT devices, and a local server. More specifically, the IoT component of the dementia-care robot includes the following components.

- **IoT Devices.** Three types of IoT devices are used: 1) Motion sensors to detect IAD's motion; 2) Multipurpose sensor to detect the door's status in wandering around protocol; 3) Smart hub for connections between sensors and SmartThings cloud.
- **SmartThings Cloud.** SmartThings cloud is a remote cloud service used as a data transition center. By using the cloud platform management tool provided by Samsung, it

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[1] https://www.twilio.com/

[2] https://www.skype.com/

[3] http://wiki.ros.org/move_base

[4] https://wiki.ros.org/gmapping

[5] http://wiki.ros.org/face_detector

[6] https://github.com/ageitgey/face_recognition

[7] http://wiki.ros.org/amcl

[8] https://www.smartthings.com/

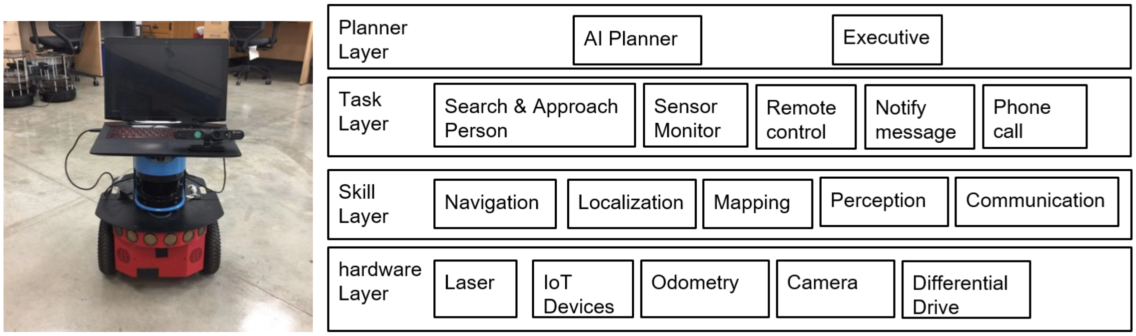


Figure 1: (L) Pioneer 3DX platform as a SAR for dementia-care (R) The ROS framework to implement care protocols

collects status information from every sensor and sends status information to our local server.

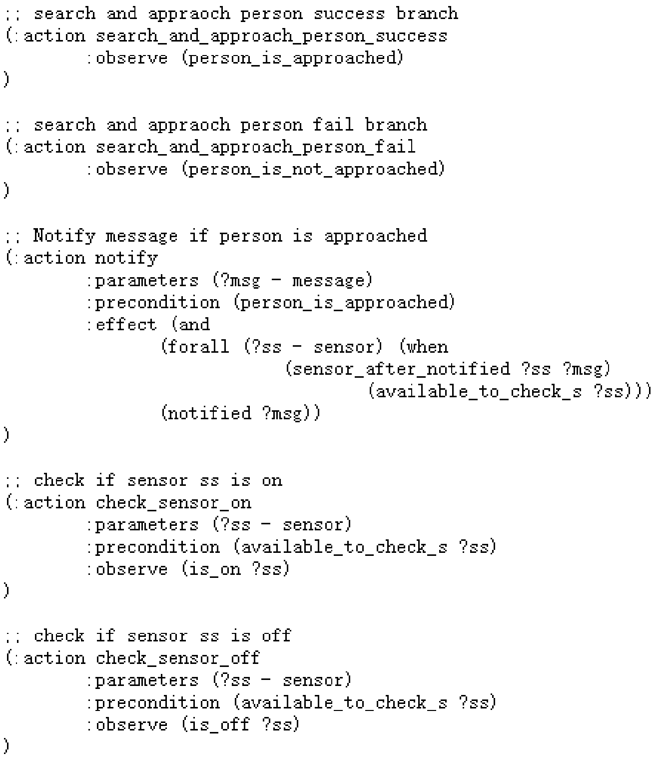
- **Local Server.** Our local server processes various requests from the robot and responses accordingly. It also communicates with SmartThings Cloud to collect information about the IoT devices.

All IoT devices are based on Zigbee (Ergen 2004) communication protocol and are also programmable by using the groovy language through developer workspace.

A Knowledge-engineering-enhanced AI planner

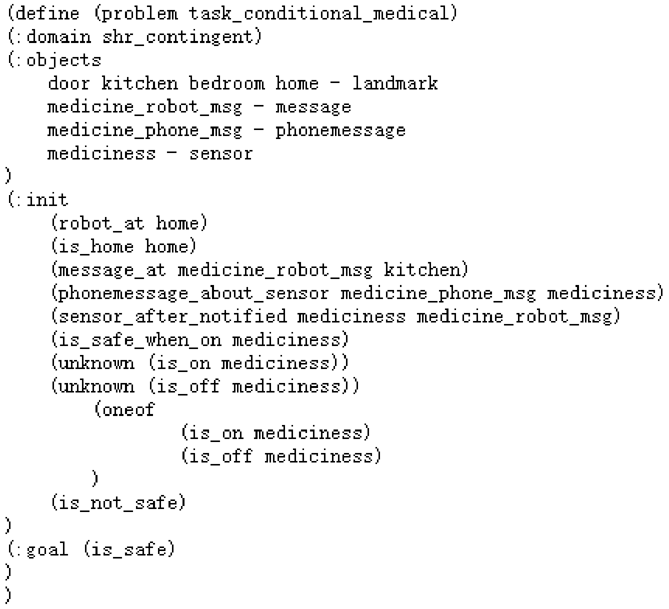
The planning system is built upon ROSPlan (Cashmore et al. 2015). ROSPlan is a planning framework that embeds PDDL planners into ROS system. It can process a predefined PDDL domain file, generate a planning problem according to the current state representation of the world, use one of the existing domain independent planners to generate a plan, and deploy the plan. There are four ROS nodes running in the AI planner: *rosplan_problem_interface*, *rosplan_planner_interface*, *roslplan_parsing_interface*, and *rosplan_plan_dispatcher*. The planner first reads in a PDDL domain file and a PDDL problem file through the *rosplan_problem_interface* node. It then calls a PDDL planner through the *rosplan_planner_interface* to solve the problem. In our framework, we use the contingent planner, *contigentFF* Hoffmann and Brafman (2005), where uncertainties in observations are accommodated into the plan through their conditional effects on the actions. After the planner generates a plan, the *roslplan_parsing_interface* will parse the plan and translate it into primitive actions that are implemented through the *Skill layer*. Then the translated plan is dispatched by the *rosplan_plan_dispatcher* node. The node schedules all the planned actions according to their time duration and the state transition.

Figure 2 shows a fragment of the baseline conditional PDDL domain file for the medication reminder protocol we described before in section III A. Here, the action *search_and_approach_person _success/fail* is used to seek the IAD in the home. The unknown knowledge of whether the IAD could be found will be revealed after this action is executed. The action *check_sensor_on/off* are used to re-



```
;; search and appraoch person success branch
(:action search_and_approach_person_success
        :observe (person_is_approached)
)

;; search and appraoch person fail branch
(:action search_and_approach_person_fail
        :observe (person_is_not_approached)
)

;; Notify message if person is approached
(:action notify
        :parameters (?msg - message)
        :precondition (person_is_approached)
        :effect (and
                (forall (?ss - sensor) (when
                            (sensor_after_notified ?ss ?msg)
                                    (available_to_check_s ?ss)))
                (notified ?msg))
)

;; check if sensor ss is on
(:action check_sensor_on
        :parameters (?ss - sensor)
        :precondition (available_to_check_s ?ss)
        :observe (is_on ?ss)
)

;; check if sensor ss is off
(:action check_sensor_off
        :parameters (?ss - sensor)
        :precondition (available_to_check_s ?ss)
        :observe (is_off ?ss)
)
```

Figure 2: A fragment of baseline PDDL domain file for medication reminder protocol



```
(define (problem task_conditional_medical)
(:domain shr_contingent)
(:objects
    door kitchen bedroom home - landmark
    medicine_robot_msg - message
    medicine_phone_msg - phonemessage
    mediciness - sensor
)
(:init
    (robot_at home)
    (is_home home)
    (message_at medicine_robot_msg kitchen)
    (phonemessage_about_sensor medicine_phone_msg mediciness)
    (sensor_after_notified mediciness medicine_robot_msg)
    (is_safe_when_on mediciness)
    (unknown (is_on mediciness))
    (unknown (is_off mediciness))
        (oneof
                (is_on mediciness)
                (is_off mediciness)
        )
    (is_not_safe)
)
(:goal (is_safe)
)
)
```

Figure 3: A PDDL problem file generated for medication reminder protocol

trieve the latest sensor data. The action *notify* is used to notify reminder message. Figure 3 shows a fragment of the PDDL problem file generated by the AI Planner for this domain. The planning process is triggered when motion is detected near the location where the medication is kept. The state of the motion sensor is continuously monitored. In the problem definition file, it is initially unknown whether the medication sensor is triggered. This uncertainty is modeled in a standard way in the initial state. It will be revealed through executing *check_sensor_on/off* actions. The goal is to achieve a safe state, i.e., *is_safe* variable needs to be true. Although the PDDL problem can be generated automatically on the fly by performing state update, it is difficult for lay users to define the domain definition file. For this purpose, We design a domain file generator to perform knowledge engineering that allows the caregivers to customize the domain definition file. The generator processes the caregivers' input, instantiates a wildcard domain template to a domain argument file, plugs in the argument file into a baseline domain file by automatically resolving conflicts and thereby generating a final customized domain file. The wildcard domain file is shown in figure 9(L). It models the requirements by a generalized operator *ACTION*, the related parameter *object*, the post-influenced operator *AS* (After Success) and *AF* (After Fail). We will explain how to instantiate this file by walking through an example in section 5. To obtain caregivers' input on customization we designed a survey-style questionnaire Most of the questions are Yes/No or multiple-choice type. A small number of questions are open-ended that allow caregivers to provide more detailed care instructions. All answers are then processed by a domain file generator. The generator is designed to hard-code some predefined logic to process the Yes/No and multiple-choice questions. For open-ended answers, we require the caregivers to write their requirements in a pre-defined language structure, so the generator can automatically retrieve the facts in the sentence (such as subjects, verbs, and objects) and then instantiate relative wild-card types, predicates, or operators.

User Study

We conducted a beta-test of the dementia-care robot prototype and the proposed AI planner through a demonstration and focus group involving informal caregivers of IAD (figure 5). Eight informal caregivers, six females and two males, participated in the study. Figure 4 lists the demographics of the participants to show the diversity in the cohort. Two major goals of the beta test were to: 1) investigate the adaptivity of the software framework and 2) explore the technical feasibility and usability of the technology at the home of care recipients (i.e. IADs).

Method

During demonstration caregivers were introduced to all functionalities of the dementia-care SAR. The caregivers then witnessed the autonomous execution of two baseline care-protocols where graduate students played the role of caregiver and IAD. The caregivers then completed a survey which reflects their thoughts on how the two baseline care-protocols need to be adjusted to suit the need of their care-recipients (i.e. an IAD).

We used the Unified Theory of Acceptance and Use of Technology (UTAUT) as the theoretical framework to guide the focus group discussion. The UTAUT facilitates our understanding of why someone intends to use a technology or information system(Venkatesh et al. 2003). Focus group questions were derived broadly using the framework's constructs of perceived expectancy (PE), effort expectancy (EE), social influence (SI), facilitating conditions (FC), technology anxiety (TA), perceived trust (PT) and perceived cost (PC). We used a mixed method to examine the convergence of qualitative data with quantitative ratings (agreement-disagreement) on these constructs. Note that we are only including the quantitative findings within the scope of this paper.

Results

Adaptivity of the AI planner The survey reveals a commonly expected customization of the medication reminder protocol: asking the robot to locate the bottle of the medication for the IAD if s/he can not find it. The generator automatically processes this requirement, retrieve a verb fact *find* and an object fact *bottle*. It instantiates the wildcard template shown in Figure 9 (L) and plugs the instantiation (figure 9 (R)) into the baseline PDDL domain file. Figure 6 shows the baseline plan and the customized plan. In a conditional plan, a branch means different observation after the execution of the action. For example the fist action in the baseline plan is to search and approach the IAD. If this action yields an observation that people is not found, the plan is to call caregiver, otherwise, the plan is to notify the reminder message.

Characteristics	**Informal Caregivers**							
	1	2	3	4	5	6	7	8
Relation	Wife	Wife	Daughter	Wife	Husband	Daughter	Wife	Husband
Care recipient's age	78	88	98	59	72	84	69	80
Care recipient's disease stage	Late	Middle	Early	Middle	Early	Middle	Middle	Late
Employed	No	No	No	Full time	Part time	Full time	No	No
Living with care recipient	Yes	Yes	No	Yes	Yes	No	Yes	No

Figure 4: Focus group participants

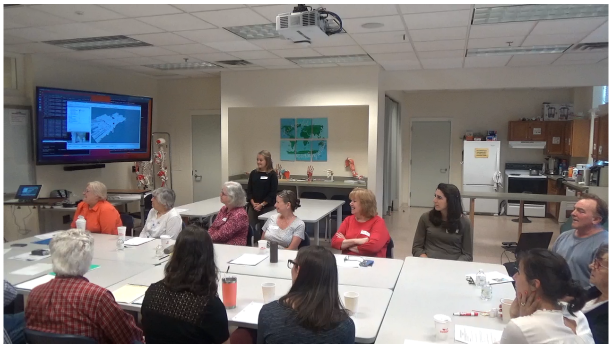
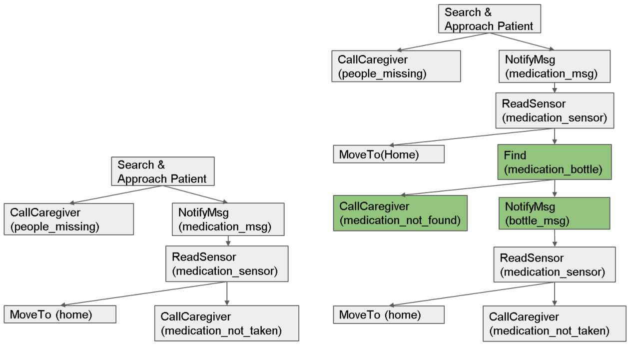
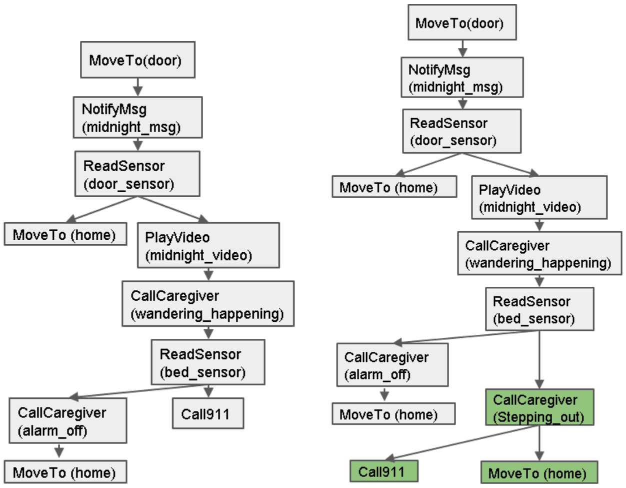


Figure 5: A group of caregivers participating in the user study



(a) (b)

Figure 6: The baseline plan (a) and the customized plan (b) for the medication reminder protocol.



(a) (b)

Figure 7: The baseline plan (a) and the enhanced plan (b) for preventing wandering protocol.

The green actions in the customized plan were added by the planner to fulfill the expectations of the caregivers automatically passed to the system from the survey response. For the preventing wandering protocol, one common requirement is to ask the robot to call the police only if the caregiver is not approachable. Figure 7 shows the baseline plan and the customized plan. The customized action is highlighted in green.

Usability analysis Figure 8 displays the agreement- disagreement (on a 5-point Likert scale) of the caregivers on the feasibility of using a dementia-care robot, when fully developed, for their homes. For performance expectancy, 7/8 caregivers agreed to strongly agreed that the SH-SAR will support their caregiving needs. All the 8 caregivers agreed to strongly agreed that they can set up the SAR-SH and use the technology at home. On the question of anxiety, 6/8 caregivers agreed to strongly agreed that they will be comfortable with the technology. On the construct of trust, 7/8 agreed to strongly agreed that it will work reliably. On the question of facilitating condition, 5/8 agreed to strongly agreed that the SAR-SH can be installed at their home with many commenting that they will need technical support to do so. As far as social influence, 7/8 caregivers agreed to strongly agreed that their family will be supportive of the use of this technology. In terms of perceived cost, 5/8 caregivers agreed to strongly agreed that the SAR-SH to be a

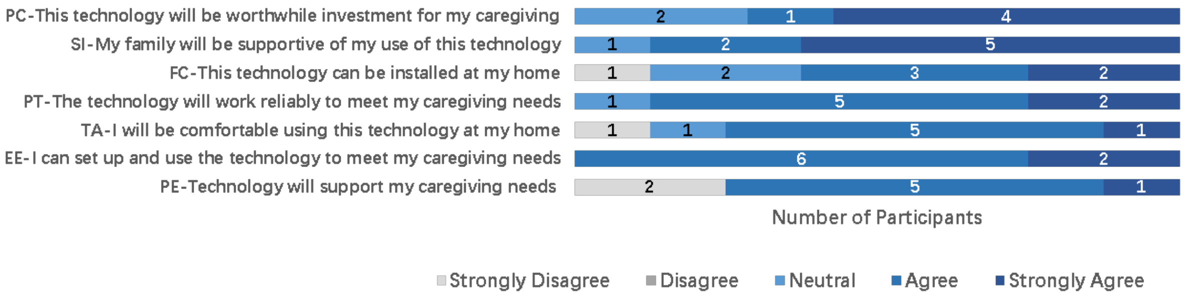


Figure 8: Agreement-disagreement (on a 5-point Likert scale) of the caregivers on the future use of the SH-SAR .

```
(define (domain shr_conditional_wildcard)

(:types
        object
        as_object
        af_object
)

(:predicates
        (ACTION_OBJECT_AVAIL ?ob - object)
        (ACTION_OBJECT_FAIL ?ob - object)
        (ACTION_OBJECT_SUCC ?ob - object)

        (AS_ACTION_OBJECT_AVAIL ?ob - as_object)
        (AF_ACTION_OBJECT_AVAIL ?ob - af_object)
)

;; Do action and check result success
(:action ACTION_success
        :parameters (?ob - object)
        :precondition (ACTION_OBJECT_AVAIL ?ob)
        :observe (ACTION_OBJECT_SUCC ?ob)
)

;; Do action and check result fail
(:action ACTION_fail
        :parameters (?ob - object)
        :precondition (ACTION_OBJECT_AVAIL ?ob)
        :observe (ACTION_OBJECT_FAIL ?ob)
)

;; enable AS_ACTION if success
(:action ENABLE_AS_ACTION
        :parameters (?ob - object, ?asob - as_object)
        :precondition (ACTION_OBJECT_SUCC ?ob)
        :effect (AS_ACTION_OBJECT_AVAIL ?as_ob)
)

;; enable AF_ACTION if fail
(:action ENABLE_AF_ACTION
        :parameters (?ob - object, ?afob - af_object)
        :precondition (ACTION_OBJECT_FAIL ?ob)
        :effect (AF_ACTION_OBJECT_AVAIL ?af_ob)
)
)
```

```
(define (domain shr_contigent_medication_enhanced_instant)

(:types
)

(:predicates
        (available_to_find)
        (bottle_is_found)
        (bottle_is_not_found)
)

(:action find_bottle_succ
        :precondition (available_to_find)
        :observe (bottle_is_found)
)

(:action find_bottle_fail
        :precondition (available_to_find)
    :observe (bottle_is_not_found)
)

(:action notifyBottle
        :parameters (?msg - message)
        :precondition (and
                      (bottle_is_found)
                      (msg_about_bottle ?msg))
        :effect (and
                 (notified ?msg)
                 (forall (?ss - sensor)
                                 (available_to_check_s ?ss)))
)

(:action call_caregiver_when_medication_is_not_found
        :parameters (?msg - phonemessage)
        :precondition  (and
                (phonemessage_about_bottle ?msg)
                        (bottle_is_not_found))
        :effect (and
                (is_safe)
                (not (is_not_safe)))
)
)
```

Figure 9: (L) Wildcard PDDL template and (R) An instantiation of the template.

worthwhile investment for their caregiving, although many commented that they needed a projected cost on the technology to clearly judge its value. In general, caregivers of individuals from early to middle stages of Alzheimer's disease and dementia perceived the potential in SAR-SH compared to those with individuals in the late stage.

Discussion

While using the proposed framework, the robot is able to customize its planner based on inputs from lay user, it is important to recognize that the domain knowledge is obtained from domain experts (through baseline domain file) and lay users (through domain plugin file). Therefore, anything beyond the domain knowledge would cause the robot fails to generate a plan, especially when a specific resource is not defined properly or not available but required in the planning model. One way to resolve this is to use a more creative planner such as CPS (Freedman et al. 2020) that can reason about the missing resources and define alternatives.

One could also enrich and scale up the current SAR system by adding more sensors and smart hardware such as smart watch, home voice assistant, sophisticated camera, etc. More autonomous robot behaviors can also be implemented as needed. However the state space for the planner grows exponentially with regard to the enriched robot functionalities. Planning with huge state space and sensing actions under partial observability are computationally challenging problems. A basic conditional planner such as *contigentFF* will be no longer capable to find a plan within reasonable time. Alternatively, we can adopt more powerful conditional planner such as PO-PRR(Muise, Belle, and McIlraith 2014) that rely on state-of-the-art techniques for fully observable non-deterministic(FOND) planning.

Conclusion

In this paper, we propose a novel AI planning-based software framework for dementia-care robots which allows lay users to change the care protocol in a seamless manner. In this approach, a knowledge-engineering technique is designed to assist lay users to generate PDDL domain files that update the high-level planner's behavior. Two dementia-care protocols are implemented to evaluate the proposed approach. We also evaluated the adaptivity of this framework through a user study where caregivers of eight IADs are invited to watch the default care protocols and re-designed the protocols according to their needs.

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