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Towards intelligent caring agents for Aging-In-Place: Issues and challenges

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Towards Intelligent Caring Agents for Aging-In-Place: Issues and Challenges

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***Abstract*—The aging of the world's population presents vast societal and individual challenges. The relatively shrinking workforce to support the growing population of the elderly leads to a rapidly increasing amount of technological innovations in the field of elderly care. In this paper, we present an integrated framework consisting of various intelligent agents with their own expertise and responsibilities working in a holistic manner to assist, care, and accompany the elderly around the clock in the home environment. To support the independence of the elderly for Aging-In-Place (AIP), the intelligent agents must well understand the elderly, be fully aware of the home environment, possess high-level reasoning and learning capabilities, and provide appropriate tender care in the physical, cognitive, emotional, and social aspects. The intelligent agents sense in non-intrusive ways from different sources and provide wellness monitoring, recommendations, and services across diverse platforms and locations. They collaborate together and interact with the elderly in a natural and holistic manner to provide all-around tender care reactively and proactively. We present our implementation of the collaboration framework with a number of realized functionalities of the intelligent agents, highlighting its feasibility and importance in addressing various challenges in AIP.**

I. Introduction

The world's population is aging. The number of persons aged 60 or above is expected to increase from 841 million in 2013 to 2 billion in 2050 [1]. Furthermore, a survey [2] shows that nearly 90% of persons aged 65 or above indicate that they want to stay in their home as long as possible, among which four of five believe their current home is where they will always live. Thus, Aging-In-Place (**AIP**) or "the ability to live in one's own home and community safely, independently, and comfortably, regardless of age, income, or ability level" [3] has received a significant amount of attention nowadays. However, there is still a huge gap between the demand for AIP and the available supporting resource: only 10% of the home improvement industry is dedicated to AIP [2]. Practical, affordable, and innovative technologies and equipment are proposed and implemented to narrow the gap.

Research on smart-home and ambient assisted living has been active in the past decade. However, many existing work focuses on providing fundamental services and upholding the physical and/or social well-being of the elderly. Because the capabilities of the elderly generally decline in all aspects (physical, cognitive, emotional, and social) as they age, they require all-around support in a holistic manner.

In this paper, we describe how the intelligent caring agents within a collaboration framework enable the elderly to maintain an active, healthy, and engaging life style in their own home by addressing the silver challenges in the aforementioned four aspects. Such an age-friendly intelligent system provides all-around tender care to the elderly including physical and cognitive assistance, constant companionship, social contact reminders, and recommendations in all aspects.

We design the intelligent agents to be heterogeneous that they have different expertise and capabilities. Each agent can work independently for the better well-being of the elderly in certain aspects. Nonetheless, they can work together in a coordinated fashion through the central controlling server. The collaboration framework is carefully designed to ensure the agents work seamlessly with each other and to resolve any inconsistency or conflict among them.

In the following sections, we present the major issues and some key technologies to address the corresponding challenges towards creating the intelligent caring agents for AIP. We then show the design principles of the collaboration framework and the intelligent agents exemplified with a number of realized functionalities. In the end, we conclude the paper.

II. Issues and Challenges for Aging-In-Place

In this section, we present the major issues and challenges faced by the elderly for AIP as follows.

(1) Physical challenges: If the elderly choose to live independently in their own home rather than nursing centres, the major concern is how to ensure their physical safety. Typically, stationary (non-slippery floor) and mobile (wheelchair) support should be provided. However, reliably notifying the others whenever an accident happens is a more challenging task.

(2) Cognitive challenges: Due to the deterioration in cognitive abilities as they age, the elderly require assistance for both short-term memory (turning off the stove) and long-term memory (remembering past events). In addition, they need to pay more effort to pick up new skills and adapt to changes.

(3) Emotional challenges: The elderly tend to respond more to the positive stimuli than the negative ones [4]. Generally speaking, elderly require constant positive companionship to keep them away from loneliness, depression, and anxiety.

(4) Social challenges: Other than home, community is also included in the concept of AIP. It is important for the elderly

TABLE I. THE KEY TECHNOLOGIES TO ADDRESS THE CHALLENGES FOR AIP

Key technologies	Major challenges to be addressed
1. Multiagent collaboration	To ensure all-around care collaboratively and resolve inconsistencies and conflicts: physical (including location, movement, health status, etc.); cognitive (when and where to provide appropriate recommendations); emotional (to provide proper companionship constantly).
2. Ambient assisted living	To assist the elderly with their physical and emotional (by sensing the mood) problems.
3. Context awareness	To provide richer contexts for physical, emotional, and social recognitions.
4. Persuasive technology	To improve the physical and emotional well-being of the elderly and keep them socially active.
5. Individual modeling	To personalize the provided services in AIP according to the individual differences: physical (navigation and assistance at home); cognitive (memory and learning); emotional (emotional illness history); and social (spiritual group and acquaintances).
6. Knowledge aggregation	To summarize cognitive knowledge and obtain common characteristics within groups.
7. Emotion recognition	To prevent emotional problems and alert the concerned parities in case of abnormalities.

to get informed on the upcoming events that they may be interested in, to maintain socially active with existing contacts, and to acquire new friends.

(5) Other challenges: To ensure safety and protect privacy, the elder's status should be all-around sensed in non-intrusive ways (minimum surveillance should be used). Moreover, the devices required to convert one's residence into an intelligent human-centered environment should be reliable and affordable.

III. KEY TECHNOLOGIES FOR AGING-IN-PLACE

In this section, we identify some key technologies and propose how these technologies should be advanced to better address the challenges faced by the elderly. The summary of the technologies and the corresponding challenges to be addressed is presented in Table I.

(1) Multiagent collaboration: Technologies in multiagent systems [5] offer various types of coordination and cooperation framework for loosely-coupled autonomous entities or agents. The overall system can be considered as a collection of intelligent agents to meet the following requirements in AIP: (a) to perform unobtrusive sensing from multiple sources; (b) to guarantee ubiquitous access to information and assistance for all-around care; (c) to better serve the elderly with specialities; (d) to create more opportunities for interactions with the elderly. Other than collaborating with shared information or knowledge, the agents should also be able to work independently with partially available information or knowledge to ensure the elder is always taken care of by at least one agent in case of possible system malfunctions. The big challenge in the multiagent collaboration system is to define efficient and feasible protocols for all agents to follow and at the same time resolve any inconsistency or conflict arose among them.

(2) Ambient assisted living: With the recent advance in ambient intelligence, sensory inputs are seamlessly collected to determine when and how to appropriately assist the elderly. However, many existing assistance is provided to sense or support the elderly in the physical aspect (mobility [6] and abnormality [7]). If adequate sensory inputs are integrated, the intelligent agents should help the elderly in more ways, such as monitoring the emotional health of the elderly as well.

(3) Context awareness: Context awareness or behavior recognition enables the intelligent agents to be aware of the previous and current situations about the elderly and the home environment. Such information can be obtained from multiple sensory devices [8] or through a personal gadget such as a smartphone [9]. However, most context awareness technologies are limited to "when", "who", "where", and "what". Higher-level behavior recognition with richer context is desired in AIP, such as "how", "with whom", "happy or sad", and "whether regular". Having more accurate and meaningful context awareness enables the agents to better understand the elderly and consequently provide more appropriate care.

(4) Persuasive technology: In terms of information communication technology, persuasion means changing the attitude or behavior of the other party through non-coercive negotiations [10]. In the case of human-agent interaction for AIP, the agents never initiate conversations for their own benefits (except for sustainability such as charging the smartphone) and they always persuade the elderly (reminder for medication, encouragement for more physical exercise, and suggestion for healthier dietary) without any form of enforcement. To perform persuasion through natural conversation [11], natural language processing, logical reasoning and inference, and natural language generation are the key building blocks of the humanoid agents. It is a big challenge to create agents with tender and caring traits to serve and persuade the elderly with different personalities, behavioral patterns, and needs.

(5) Individual modeling: The sensory inputs non-intrusively collected from the elderly and the home environment should be archived in a dedicated server together with the known information (personal preference and medical history). More importantly, high-level individual user profiles should be modeled based on all available knowledge. With individual modeling, the intelligent agents can serve more effectively at appropriate time to avoid being annoying [12] and provide better personalized applications [13] systematically with richer context. However, autonomously mining the individual user pattern from observation and interaction is never an easy task.

(6) Knowledge aggregation: There are two ways to aggregate knowledge within AIP. First, with the proliferation of crowdsourcing platforms, it is possible to elicit the help of the crowd to guide the elderly to learn up-to-date knowledge and practice current technologies in more comprehensive manners (instructions can be summarized by applying computational intelligence techniques [14]). Therefore, instead of wasting time on traveling and queuing, the elderly may stay at home while enjoying different online services through the intelligent agents, such as paying bills through Internet banking, playing an online physical rehabilitation exercising game, or watching a video on how to prepare a healthy meal. The other way of knowledge aggregation for AIP is more towards big data analysis on user patterns. If anonymous user data is collected

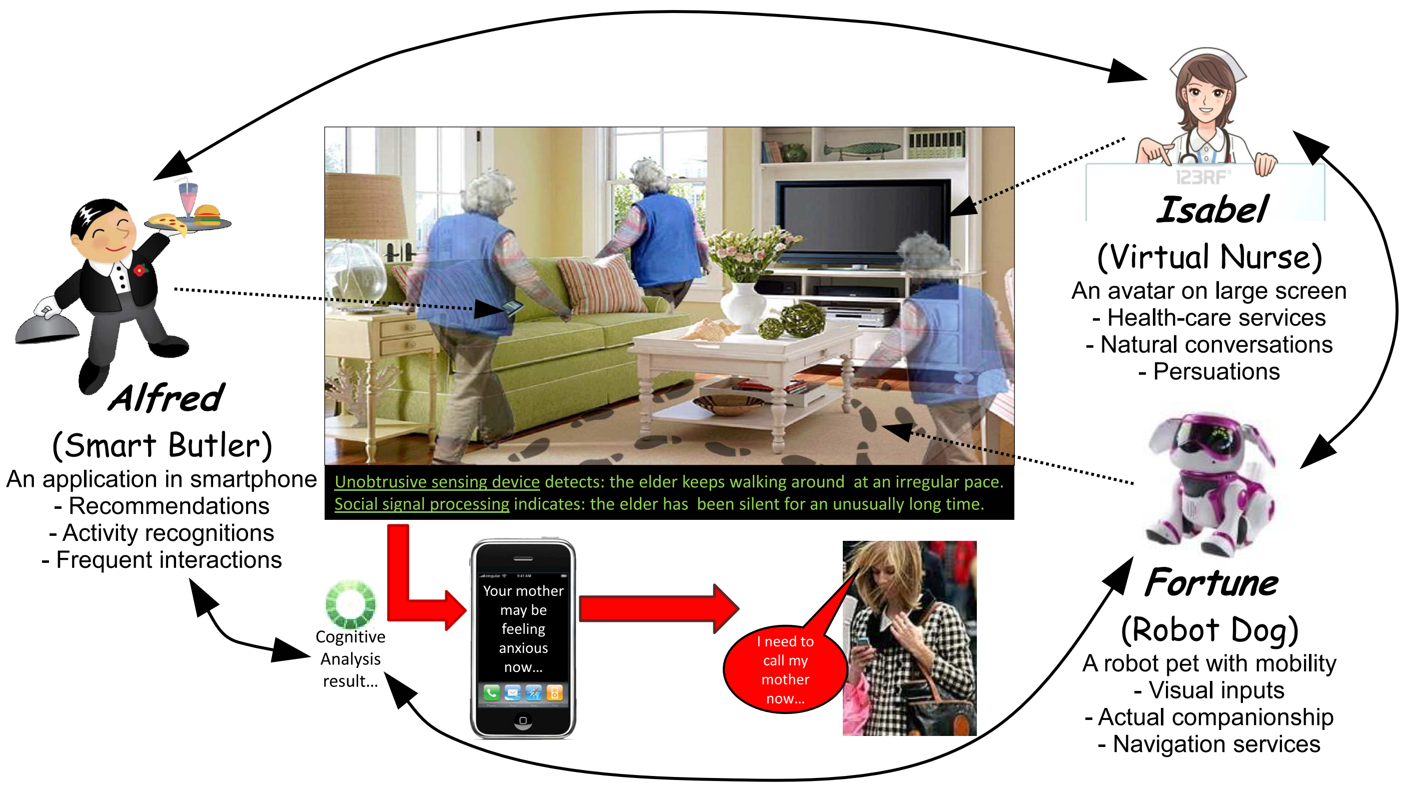


Fig. 1. An example demonstration of the collaboration framework consisting of three intelligent agents for tender care in AIP.

TABLE II. MAPPING THE DESIGN PRINCIPLES TO THE CORRESPONDING KEY TECHNOLOGIES

Design principles	Corresponding key technologies
1. Diverse domain knowledge	Multiagent collaboration, ambient assisted living, individual modeling, knowledge aggregation, and emotion recognition.
2. Independent functionalities	Multiagent collaboration and context awareness.
3. Natural interactions	Persuasive technology, individual modeling, and emotion recognition.
4. Special requirements	Ambient assisted living and individual modeling.
5. Social activeness	Context awareness, persuasive technology, and individual modelling.

and analyzed, the results are helpful to recognize different behavioral patterns among the elderly and consequently provide more related services to each individual (similar to give merchandise recommendations during online shopping [15]).

(7) Emotion recognition: Many existing work focuses on the personification of the virtual agent through human-agent interactions [16]. Only a few focus on the mood awareness of the human [17] (besides emotion recognition through facial expressions and speech signals). The major challenge in emotion recognition is how to collect adequate reliable sensory inputs in non-intrusive ways to assess the user emotion. However, to provide effective emotional support and deliver human-like virtual companionship, mood awareness of the elderly is a necessary module for the intelligent caring agents.

IV. DESIGN PRINCIPLES

In this section, we present the design principles of the intelligent caring agents for AIP within a collaboration framework. Fig. 1 illustrates a multiagent system consisting of three agents: a smart butler residing in the smartphone, a virtual nurse residing in the computer, and a robot dog with mobility. The assumptions taken are: (a) the elder always carries the smartphone (smart butler application activated) on the waist belt with a holder (for activity recognitions from the sensors embedded in the smartphone [9]); (b) the virtual nurse is activated during day-time and could appear on one of the display panels (computer monitor, TV, and any other mobile or stationary screens) at any time; (c) the robot dog, which can move freely on the floor and provides visual inputs, is activated upon commands (from the elder or agents) to reduce unnecessary energy consumption.

Based on the application framework illustrated in Fig. 1, we identify the major design principles as follows. The summary of mapping the design principles to the afore-reviewed corresponding key technologies is given in Table II.

(1) Diverse domain knowledge: Each agent has a unique set of knowledge and expertise to support the elder in different aspects. For example, the butler takes care of the activity plans of the elder and gives recommendations; the nurse is an expert in health-care and is responsible for providing health related advices; the robot dog provides actual companionship (touch) and gathers visual inputs for activity recognition, if permitted. All three agents collaborate together to sort out the agreed priorities of different individual tasks to avoid confusions and resolve conflicts (elaborated in Section V-F) based on the individual expertise and the reliabilities of the sensory inputs.

(2) Independent functionalities: Each agent is able to function independently to support the elder but at the same time plays its part contributing to the overall goal of all-around sensing and care. For example, when the elder goes out, the butler residing in the smartphone is relied on. When the elder goes to the bathroom without bringing the smartphone, the robot dog can move over to check the status of the elder.

(3) Natural interactions: The interactions between the elder and the agents should be natural. For example, reminders and recommendations can be conveyed to the elder through conversations in natural language. Although full understanding and generation of the natural conversations remain as big challenges, the system can use certain existing technologies [11] for natural language processing, parsing, and generation.

(4) Special requirement: Special needs of the elder can be identified and catered by different agents. For example, if the elder suffers from dementia, the priorities of reminders should be increased by the butler, who should also attract more attention (vibration and sound); if the elder requires intensive health monitoring, the nurse should be more active and may require additional wearable sensors (to measure heart rate and blood pressure) and physically installed ones (to detect fall down or other critical conditions); if the elder suffers from certain physical incapability such as poor eye sights, the robot dog plays a more important role to assist in navigation and should proactively clear hazardous obstacles along the paths.

(5) Social activeness: Agents must help the elder to maintain an active social life. With the Internet connectivity of the butler and the nurse, the elder could easily remain active on social network service platforms. If the elder has not been responsive to friends' updates or has not logged into his or her own account recently, persuasive conversations are initiated. Furthermore, if evidence shows the elder has any abnormal conditions (both physically and emotionally), family members, neighborhood watchers, or other concerned parties (nearest hospital, police station, or caring service providers) should be notified through text messages, email alerts, or direct calls.

V. System Implementation

Although the realization of the overall system is still ongoing, we present the implemented modules of the butler, the nurse, and the collaboration framework in this section.

A. *Implementation platforms*

Due to the distributed nature of the multiagent system and the diversity of the challenges to be addressed, different components require different developing tools and programming languages in different platforms. The smart butler is implemented in Java and XML as an Android application for smartphones and tablets. The virtual nurse is implemented in C# using the Unity 3D engine as a computer program. The collaboration proxy is implemented using the NodeJS framework (a server-side JavaScript platform).

B. *Discussion on feasibility*

There is a common stereotype that the elderly are not receptive to advanced technological gadgets. However, although less confident than younger people, elderly who have experiences of using the modern gadgets generally hold more positive attitudes and greater confidence [18]. If computers (extensible to smartphones) are modified according to the specific needs of the elderly with simpler interfaces that follow the natural mental concepts, the elderly can benefit much from them [18]. Moreover, the usage of Internet, computers, and social network service platforms among the elderly keeps increasing over the past decade [19]. Therefore, deploying the agents in the smartphone and computer platforms is a feasible and practical way to assist the daily lives of the elderly.

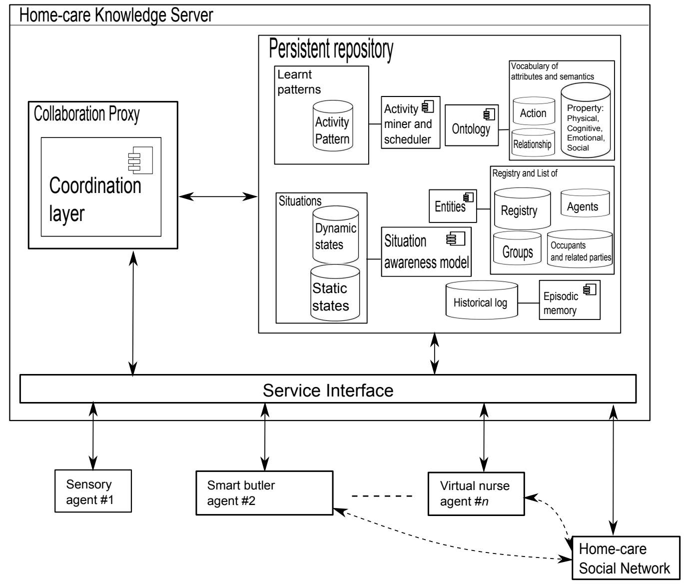


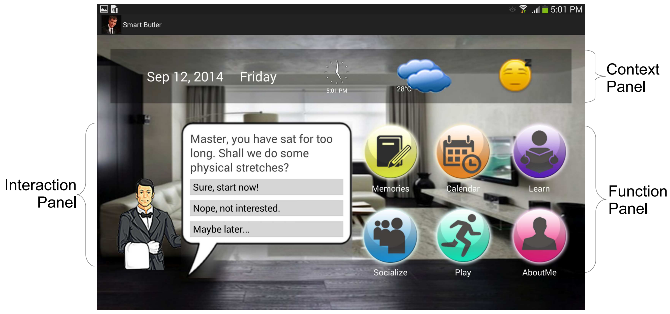
Fig. 2. The overall system architecture.

In addition, our proposed collaboration framework consisting of intelligent agents does not involve much financial costs. Because the current smartphone penetration rate in many developing and developed countries is high [20], many elderly can use the smartphones that they already have. Moreover, as discussed earlier that each agent in the collaboration framework can work independently, excluding the expensive robot dog does not make the overall framework obsolete.

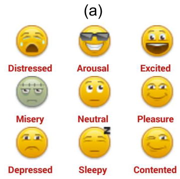
C. *Overall system architecture*

The overall system architecture is presented in Fig. 2. The central controlling server (*Home-care Knowledge Server*) consists of the following components: (1) the collaboration proxy, which ensures the cooperation among the agents and resolves any inconsistency or conflict (elaborated in Section V-F); (2) the situation awareness model, where both the dynamic situation of the elder as well as the environment (the elder is now sitting in the study-room using computer) and the static information (the living-room is next to the master bedroom) are stored; (3) the recognized activity patterns of the elder (normally wakes up at 6:30 am in the morning during weekdays); (4) the ontology library, where the vocabulary of the attributes and semantics is stored; (5) the entity library, where the details of all subjects are stored; (6) the history log, where all the past information is archived; (7) the service interface, which flexibly connects all agents to the system.

Other than the smart butler (elaborated in Section V-D)



(a)



(b)

Fig. 3. Different modules of the smart butler. (a) the layout of the graphical user interface. (b) the drop-down list of emoticons for mood annotation.

and the virtual nurse (elaborated in Section V-E), sensors can also be considered as (non-intelligent) agents. Moreover, it would be interesting to enable frequent interactions between the agents and the *Home-care Social Network*, which consists of the concerned parties of the elder (relatives, friends, caretakes, and people from nearby police station and hospital). In this way, the intelligent agents would be more human-like and the concerned parties can constantly query the status of the elder through the agents to avoid unnecessary interrupts.

D. Smart butler

The graphical user interface of the smart butler is shown in Fig. 3(a). The background picture shows the elder is currently in the living-room. The context panel consists of three parts: (1) the current date and time; (2) the real-time weather and temperature taken from the official website; (3) the emoticon that reflects the affective state of the elder. The emoticon button allows the elder to explicitly annotate his or her affective state. If the button is pressed, a drop-down list will be displayed (see Fig. 3(b)) for the elder to annotate one of the nine affective states. All the chosen affective states follow the well-known circumplex model of affect [21]. A computational activity-affect model [22] has been used to predict the elder's affective state (based on the recognized activities that the elder performed or experienced), which will be automatically updated in the interface. The computational model (in neural network form) imports the initial domain knowledge from the published work in psychology and gerontology and takes the mood annotations and keyword detections as the training signals. After adequate training, how the recognized activity affects the mood of the individual elder can be successfully modeled. By utilizing the individual activity-affect model for mood awareness of the elder, more specific and appropriate tender care can be provided (more details are available in [22]).

The function panel of the smart butler shown in the lower right part of Fig. 3(a) consists of six major functionalities provided to the elder: (1) "Memories" stores and retrieves the episodic memory of the elder with the associated affective states (annotated or estimated) in multimedia formats (pictures, videos, and music); (2) "Calendar" stores the personal schedule of the elder, upon which reminders with dynamically changing priorities will be delivered at the corresponding time; (3) "Learn" helps the elder to acquire new or review mastered skill sets either locally (videos recorded by family members) or online (step-by-step instructions retrieved from trustworthy crowdsourcing platforms); (4) "Socialize" allows the elder to call, message, or interact with (through social network service platforms) others; (5) "Play" streams the videos (online) for physical exercise (Yoga, dance, and Tai-chi), links to various mental exercising games (online) as cognitive stimuli [23], and offers different types of leisure activities (Karaoke and a number of selected games that are suitable for the elderly); (6) "AboutMe" keeps the personal profile and the contacts of the concerned parties. We try to integrate all the smartphone applications that the elderly normally use (call, message, Internet surfing, and online social networking) and our implemented ones (there are a great number of games developed for the elderly by our research centre[1]) into the sub-functions of the smart butler. Therefore, the elderly would only need to interact with the smart butler for all kinds of usages of the smartphone.

The interaction panel of the smart butler shown in the lower left part of Fig. 3(a) illustrates how the smart butler interacts with the elder (currently, a text message is provided as the context and buttons are provided to capture the corresponding responses). In this panel, the smart butler always initiates the interactions. On the other hand, in the function panel, the elder decides which particular type of service is needed. However, through the interaction panel, the elder can also be directed to one of the functions provided in the function panel. When necessary, a pop-up frame with more detailed or more critical information can be shown to the elder.

We categorize all the recommendations of the smart butler (delivered in the interaction panel) based on the corresponding types of the silver challenges (see Section II) they aim to address. Therefore, based on the situation awareness and the learnt activity pattern of the elder (see Fig. 2), the smart butler can initiate the following five types of recommendations:

(1) Physical recommendations: Based on the sensors embedded in the smartphone, the smart butler knows the motion and location [9] of the elder. Therefore, it is able to automatically generate physical recommendations such as help functions whenever a fall-down is detected, physical exercise encouragements when the elder has not been physically active for a relatively long time (see Fig. 3(a)), and suggestions for resting based on the learnt activity pattern of the elder.

(2) Cognitive recommendations: In the cognitive aspect, the smart butler reminds the elder whenever necessary. The automatically generated reminders or suggestions include asking the elder to update his or her diary at specific time, reminding the elder to take medication or get ready for appointments based on the calendar, and querying the elder whether he or she left something behind or forgot to turn off certain devices, such as light, TV, and stove.

(3) Emotional recommendations: It is mentioned earlier in this section that a computational model [22] is used to

[1]Joint NTU-UBC Research Centre of Excellence in Active Living for the Elderly (LILY): http://www.ntulily.org/

predict the affective state of the elder if adequate training signals are collected. Therefore, the smart butler is able to automatically generate emotional recommendations such as asking the elder to provide mood annotations (see Fig. 3(b)) for rewards, offering appropriate suggestions for the emotional wellness of the elder (tell a joke to cheer up or play a peaceful music to calm down), and notifying the concerned parties whenever it detects any emotional abnormality.

(4) Social recommendations: In the social aspect, the smart butler promotes social activeness to the elder. The automatically generated suggestions include asking the elder to contact others if he or she has been socially inactive for a relatively long time, notifying the elder if others (family members and friends) are available online for a chat or a game, and informing the elder all the related upcoming social events (from others or the official websites).

(5) Sustainable recommendations: In the sustainable aspect, the smart butler ensures the proper functionalities of itself and the overall system. The automatically generated messages include asking the elder to charge the smartphone, suggesting the elder to always bring along the smartphone (for non-intrusive sensing and ensuring deliverable interactions), and querying the elder for any system malfunction (sensor connection failures or other hardware problems).

Although the priorities of the recommendations delivered by the smart butler are hard-coded currently, the priority of certain recommendation can be increased dynamically according to the sensed context. An example is given as follows: (a) low-level priority: a reminder will be automatically generated five minutes before the scheduled time for the elder to take certain medication. Messages of this priority can be ignored and will be discarded after certain period of time; (b) medium-level priority: a subsequent reminder will be automatically generated five minutes after the scheduled time to confirm whether the elder has taken the medication. Messages of this priority are delivered with vibration and alarm to attract more attention and will remain active in the interaction panel of the smart butler (other applications in the smartphone can still be activated) until the elder responses; (c) high-level priority: a final reminder will be automatically generated if the smart butler has not received any response from the elder for certain period of time. Messages of this priority initiate communications with other agents or the concerned parties. Moreover, the screen of the smartphone will be locked until the elder responses.

E. Virtual nurse

The virtual nurse (see Fig. 4) is an agent specializing in health-care. Its 3D high-resolution avatar (implemented using the Unity 3D engine) is displayed on the 2D large screen. This design enables the virtual nurse to show more expressions (facial expressions, body postures, and hand gestures) during the natural conversations with the elder for conveying its emotional response. Other than health related support, the virtual nurse also provides a wide range of care-giving functions: (1) querying the well-being of the elder; (2) giving medication reminders; (3) encouraging healthier living style in a holistic manner, such as recommending physical and mental exercises when necessary, introducing healthier dietary, promoting life-long learning, and suggesting social engagements with others;

Fig. 4. The virtual nurse proactively provides a suggestion for exercises.

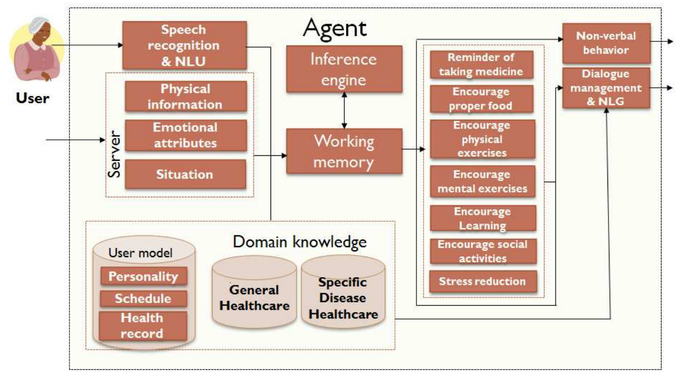


Fig. 5. The system architecture of the virtual nurse.

(4) providing suggestions for stress reduction. Some of the functions are shared with the smart butler.

To make the virtual nurse not only look realistic but also have natural and human-like behaviors, the following three key characteristics of modeling realistic agents [24] are emphasized: (1) *autonomy*: agents can function on their own; (2) *interactivity*: agents can interact naturally with other agents, human players, and the environment; (3) *personality*: agents can exhibit human traits and characteristics. Working towards these challenges, we propose a brain-inspired agent architecture (using the fusion ART [25] neural network for knowledge storage, retrieval, and adaptation) to integrate autonomy, natural language interaction, and human-like personality.

The system architecture of the virtual nurse is presented in Fig. 5. The intention or response of the elder is interpreted from the input (either text or speech) by the *Speech Recognition and Natural Language Understanding (NLU)* module. After processing the information, the virtual nurse answers or responses to the elder (both text and speech) through the *Dialogue Management and Natural Language Generation (NLG)* module and animates its facial expression, body posture, and hand gesture through the *Non-Verbal Behavior* module. The speech-to-text and text-to-speech functions are realized by incorporating the MicroSoft Speech Recognition tool.

Fig. 6. The virtual home environment and the avatar of the elder.

F. Collaboration proxy with simulations

The overall system implemented for AIP consists of intelligent caring agents that each serves the elder in a holistic manner. Besides maintaining the accurate perception or beliefs about the situation of the elder and reactively producing relevant or meaningful responses, all agents have social (communication) capabilities ranging from proactively recommending the appropriate options for food or exercise to persuading the elder to change his or her decisions. This implies that the system needs to maintain commitments and represent the respective beliefs, wants, and intentions [26]. For example, when an agent generates an important reminder for taking medication, the system needs to ensure that the elder performs the reminded action (by answering the specific question), before allowing all agents to interact with the elder for other tasks with lower priority.

An agent by itself is a fully functional application to serve the elder in a holistic manner, which may be deployed dynamically in multiple platforms. However, the agents should communicate with each other to exchange information, coordinate their activities, and adapt their roles within the multiagent system [5]. In other words, they must be able to work together in a coordinated fashion when coexist.

We develop each intelligent agent based on the standard framework in which there is an interface that flexibly connects the agents to the overall system. Because each agent may need to process the mental abstraction of the elder, we use a nested structure of the elder's mental attributes as the main knowledge representation to be exchanged between the agents for coordination and collaboration [27]. The standard protocol supporting the representation of different aspects is presented as follows: (1) the mental modalities of belief, desire, intention, and capability; (2) the individual and group mental attributes; (3) the temporal modalities of present, near future, and persistent event for all mental attributes; (4) the possibility of a future event and the intentional states.

We have developed a simulation environment to test the framework and explore different coordination and collaboration situations. The simulation environment (implemented using the Unity 3D engine, see Fig. 6) is a virtual home in

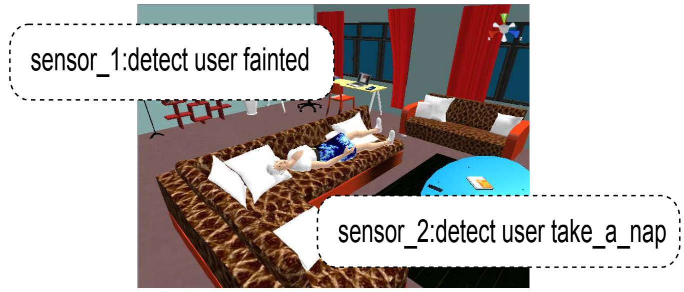


Fig. 7. An example of the inconsistency situation.

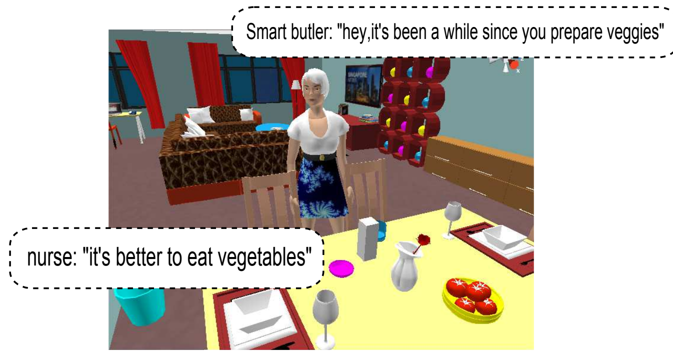


Fig. 8. An example of the supportive dialogue situation.

which the elder avatar performs certain daily-tasks (controlled manually or by generated routine). Using the simulation environment, we can show different types of interdependency among the agents as follows:

(1) Inconsistency: Two or more agents have contradictory beliefs. For example: agent i says the elder is unconscious but agent j says he or she is fine (see Fig. 7).

(2) Conflict: Two or more agents have different goals that may contradict each other. For example: agent i intends to suggest the elder to have a rest after taking medication but agent j recommends to play a game.

(3) Cooperation: Any agent can help the others. For example: agent i wants to but cannot know the elder's current location, then agent i queries the location from agent j (through the service interface, see Fig. 2).

(4) Support: When one agent makes certain suggestion, another agent generates a supporting recommendation. For example: agent i suggests the elder for certain healthier dietary and agent j supports agent i by stating that the elder has not eaten that for a long time (see Fig. 8).

We implement a collaboration proxy to continuously collect the standardized information updates from all the intelligent agents, detect any belief inconsistency, possible conflict, and potential for cooperation, and send information to the related agents to resolve the situation (if necessary). In other words, the proxy manages the collaboration among all the agents by ensuring the consistency of their aggregated mental states [28]. The pseudo code of the coordination proxy is given in Algorithm 1. The proxy is designed to be scalable, which means it can be directly applied to a group of agents (other than the smart butler and the virtual nurse).

Algorithm 1 The coordination proxy of all agents

WHILE True
  Receive message Msg_a from agent a
  IF Msg_a is an assertion
   Compare Msg_a with all other assertions in $\mathcal{M}$
   IF Msg_a is a belief and inconsistent with $Msg'_b \in \mathcal{M}$
     Notify a and b about inconsistency
   IF Msg_a is a goal and conflicting with $Msg'_b \in \mathcal{M}$
     Notify a and b about the conflict
   IF Msg_a is a desire and a is incapable to achieve it
     IF from $\mathcal{M}$, there is agent b capable to achieve it
       Notify b to help a for Msg_a
  Update $\mathcal{M}$ based on Msg_a

VI. Conclusion

In this paper, we outline the issues and challenges in the emerging application domain of aging-in-place and how they can be addressed by advancing and applying the identified key technologies. More importantly, we present a collaboration framework consisting of intelligent caring agents with different expertise to provide all-around tender care to the elderly. Although the overall framework is designed for the elderly who generally require frequent attention, constant companionship, and deep understanding, it can be easily altered for similar contexts (patients who require special treatments at home) or adapted generally for monitoring the well-being of everyone in all the physical, cognitive, emotional, and social aspects. We have already implemented a number of functionalities of the intelligent agents and the collaboration framework and we are currently working towards realizing all the rest proposed functionalities. In summary, we do believe the advances in aging-in-place will greatly benefit from the state-of-the-art research work in the field of computational intelligence.

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