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A Robotic Coach Architecture for Multi-user Human-Robot Interaction (RAMU) with the Elderly and Cognitively Impaired*

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Abstract— **The population in the US is aging rapidly. By 2030, twenty percent of the US population will be 65 years or older. Both physical and mental health conditions impact older adults' overall quality of life. Recently, Socially Assistive Robotic (SAR) systems have been developed to augment the existing resource-strained healthcare facilities. Several SAR systems were developed to maintain and/or improve older adults' physical, cognitive functioning and social well-being. However, there is limited work on closed-loop SAR systems that can simultaneously engage more than one older adult. In this paper, we developed a robotic coach architecture, RAMU, for interacting with two older adults. In addition, a preliminary study was conducted with four pairs of older adults with and without cognitive impairment. Survey results indicated that participants enjoyed interacting with the robot as well as with each other.**

I. Introduction

The population in the US is aging rapidly as the baby boom generation ages. In 2010, thirteen percent of the population was age 65 or older and this number will grow to nearly 20 percent by 2030 [1]. With aging, there is an increase in comorbid illnesses with the concomitant decreasing ability to perform instrumental activities of daily living, such as shopping or cooking, as well as diminished ability to perform activities of daily living, such as bathing and dressing. With advancing age is also the likelihood of developing dementia, with the prevalence of Alzheimer's disease alone projected to increase 35 percent by 2030 and 110 percent by 2050 [2]. Dementia is a neurocognitive disorder that affects memory, language, problem-solving and other cognitive skills related to everyday activities. Older population with Mild Cognitive Impairment (MCI) also show a decline in cognitive function and are at higher risk of later progressing to dementia [2]. Non-pharmacologic interventions such as physical exercise, mentally stimulating and socially engaging activities have been targeted to older populations for the purpose of maintaining or improving functioning, social well-being, and overall quality of life [3, 4]. Given the high health care expenditure at older ages, the shortage of geriatric health care professionals, and the substantial economic, physical and emotional burdens on informal family caregivers, technological strategies that could augment the current care setting and enhance physical, cognitive and social activities among older adults are in urgent need.

One technological strategy, socially assistive robotic (SAR) systems, has been promoted in recent years as an approach to support both older adults and their caregivers. Extensive work has been carried out to study the efficacy of animal-shaped robots (e.g., Paro, a baby harp seal [5]) in providing social support for and alleviating negative behaviors of older adults [6]. Positive effects, including an increase in engagement activities and a decrease in psychological stress reactions, were reported after participants were exposed to and/or interacted with these robots [7]. Lately, researchers have investigated the use of more advanced SAR systems for elder care. Such systems take the role of a coach or a partner, initiate the interaction, and adapt system behaviors during the interaction for the purpose of improving older adults' physical, cognitive, and psychological health. Several SAR systems were built to encourage older adults to perform physical exercises, monitor their performance and correct their movements [8-11]. Tapus et al. developed a robot testbed, Bandit II humanoid robot on a Pioneer mobile base, to facilitate older adults during post-stroke rehabilitation and a cognitive stimulation activity through encouragement and motivation [12]. McColl et al. developed robot Brian 2.1 for assisting meal-eating activity and memory card game activity and tested system acceptance at a long-term care facility [13]. Preliminary results indicated participants' engagement and compliance when interacting with the robot. However, the bulk of the SAR systems reported to date were designed for one-on-one interaction with the robot. There are limited studies on SAR systems interacting with a group of older adults. Group robotic exercise coaches developed by Matsusaka et al. [14] and Bäck et al. [15] demonstrated exercise routines to multiple older adults but did not provide task related feedback. Kanoh et al. programmed YORISOI Ifbot to conduct multiple engagement activities with a group of five older adults [16]. A human assistant was included in the interaction loop as a representative for the older adults group. Another multi-user SAR system, Tangy, was developed by Louie et al. [17]. Tangy had the capability of scheduling and leading bingo games and providing individualized assistance one at a time.

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In this paper, we describe the development of a Robotic coach Architecture for Multi-User (RAMU) human robot interaction with an eye to foster human-human interaction, particularly among older adults. A small user study was conducted to understand the tolerance and acceptance of RAMU by the older population with and without cognitive impairment. As a preliminary study, the system was not designed with the intention to improve social interaction or cognitive functioning of older adults. RAMU had the capability of playing a "Simon Says [18]" activity with two older adults and providing prompt feedback to each individual or the pair as a whole. Compared to the existing multi-user SAR systems, RAMU could adapt its behavior based on human interaction, did not require a human assistant to mediate the interaction, and was able to monitor performance of both older adults. We conducted a preliminary study with four pairs of older adults in order to investigate whether older adults would engage in multi-user interaction, would interact with each other in addition to the robot, and to obtain feedback to improve the system design. The ultimate goal of this work is to foster interpersonal social interaction between older adults themselves with the aid of the robot whose role would gradually fade away as people start interacting with each other. The rest of the paper is organized as follows. Section II presents the robotic coach system architecture RAMU and the implementation details. Section III describes the experimental protocol and participant statistics. We also provide the experimental results and discuss their implications in this section. Finally, we conclude the paper in section IV with a discussion on the contributions of the current work and how this work will be extended in the future.

II. Robotic Coach System

RAMU was composed of four modules which are shown in Fig. 1: a Sensing module, a Low-level Robot Controller module, a Graphical User Interface (GUI) module, and a Supervisory Controller module. The Sensing module served as the perception component of RAMU. It could detect the upper body movements and button click inputs from a Razer Hydra, which is an input device with two game controllers that can provide hand motion, orientation and button inputs [19], of two older adults simultaneously or in a designated order. The Low-level Robot Controller module was responsible for implementing the robot's movements and speech determined by the Supervisory Controller module. The GUI was designed to allow an administrator to initiate and monitor the interaction. In addition, the control logic of the Simon Says activity and the robot's feedback were handled by the Supervisory Controller module as well.

A. Interaction Scenario

We used the humanoid robot NAO (www.aldebaran.com) for the triadic human robot interaction (HRI) scenario. NAO is a 57.3 cm tall robot with 25 degrees of freedom. It is fully programmable and is being widely used by researchers and educators. NAO robot platform is equipped with a variety of sensors and embedded with software modules for communication such as text-to-speech. We acknowledge that NAO has limitations, including: small size, lack of facial expressions, limited range of motion in the joints, and eye gaze control relative to its head (i.e., head turn is necessary to approximate a gaze shift). Despite these limitations, NAO is suitable for this study given its affordability, user-friendly appearance, smoothness and precision of its movements, and most importantly its open architecture, which allows us to develop customized robot behaviors and integrate other interactive devices with the robot.

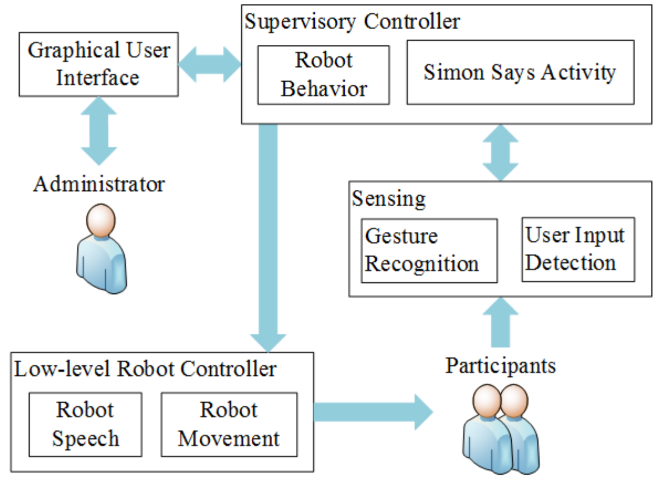

Figure 1. System architecture.

The Simon Says activity is a group interaction game beneficial for older adults' reflex skills, memory, as well as physical function. During this game, one player is the leader and demonstrates a movement. If the leader introduces the movement with "Simon says", e.g., "Simon says raise both of your arms up.", the rest of the players must imitate the action. If the leader starts the statement without "Simon says", the rest of the players should not follow. In this version of the Simon Says game that we have designed, older adults keep playing even if they fail and each individual and the robot take turns to play the leader role. This activity requires older adults to quickly recall the names of the body parts and interact with the robot as well as the other player. It is appropriate for older adults with cognitive impairment and is flexible with the number of movements as well as the number of older adult participants.

B. Interaction Interfaces

Older adults interacted with RAMU by using a Razer Hydra and a Microsoft Kinect for Windows RGB-D sensor, and receiving audio and visual feedback from NAO. The framework of the Low-level Robot Controller module is illustrated in Fig. 2. The robot was controlled through remote call using Simple Object Access Protocol (SOAP) over the local area network. We created a Motion proxy and a TextToSpeech proxy to the NAOqi's ALMotion module and ALTextToSpeech module and invoked the methods contained in the modules by attaching the proxies to the current NAOqi broker. The NAOqi software, including the NAOqi broker, modules, and methods, were running on the NAO robot, whereas the proxies existed in the PC side. The three components at the top of Fig. 2 were specified by the Supervisory Controller module to control the movement and the speech of NAO. The lists of joints, angles, and times were provided to control the robot's movement and the speed of the movement whereas the content in the string that sent to the TextToSpeech proxy controlled the robot's speech, voice

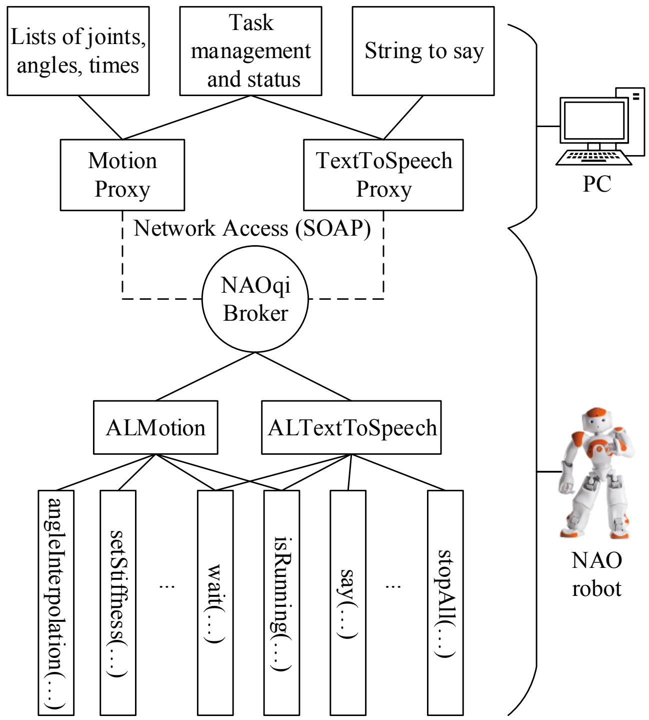

Figure 2. Low-level Robot Controller framework.

pitch, and speaking rate. NAOqi software allows the methods to be invoked as blocking calls, i.e., execute only one task, or non-blocking calls, i.e., execute multiple tasks concurrently. The tasks were monitored, made to wait or stop using task IDs.

The Kinect for Windows sensor was used to recognize older adults' arm movements over time. Its skeletal tracking algorithm can recognize two skeletons simultaneously at a frame rate of 30 Hz. The locations of older adults' arms at each Kinect frame were represented by the absolute positions of the left and right shoulder joints, elbow joints, and wrist joints with respect to the Kinect coordinate space, as shown in Fig. 3. The gesture recognition algorithm for raising one hand was adapted from the rule-based Finite State Machine (FSM) method developed by our group [20]. Given the gesture features within a sliding window whose size varied from one to five seconds (30 to 150 Kinect frames) increasing by one second, we checked whether the gesture rule, which consisted of smaller goals we referred to as checkpoints, were satisfied (Table I). The gestures must lie within the regions of interest (ROIs) when these checkpoints were reached. There were two ROIs, a vertical ROI and a horizontal ROI, defined for the vector $\overrightarrow{SW} = W_J - S_J$ to avoid awkward movements or movements NAO could not copy smoothly. For example, the vertical ROI for the right arm ignored the XZ plane whereas the horizontal ROI ignored the second and third octant of the three-dimensional space, e.g., the gray shade in Fig. 3. The sliding windows updated every Kinect frame.

The Razer Hydra consists of two separate controllers and a base station. During the HRI, each older adult held one controller and pushed down the trigger button on the controller to indicate end of speech, affirmative replies, or

TABLE I. RAISING ONE HAND GESTURE RULE

cp1	The wrist joint (W_J) is above the elbow joint (E_J).
cp2	W_J moves upward for at least 0.2 m over ten frames ($10f$).
cp3	E_J is above the should joint (S_J) and the elbow angle (E_A) is greater than 90 degrees.
cp4	Failed if both hands reach cp3 over $5f$.
cp5	Side to side W_J movement is less than 0.2 m over $10f$.
Rule	$(W_J.Y > E_J.Y)_{10f}$, $(\max(W_J.Y) - \min(W_J.Y) \geq 0.2)_{10f}$, $(E_J.Y > S_J.Y \wedge E_A > \pi/2)_{10f}$, $\neg(L_{cp3} \wedge R_{cp3})_{5f}$, $(\max(W_J.X) - \min(W_J.X) < 0.2)_{10f}$

cp: checkpoint

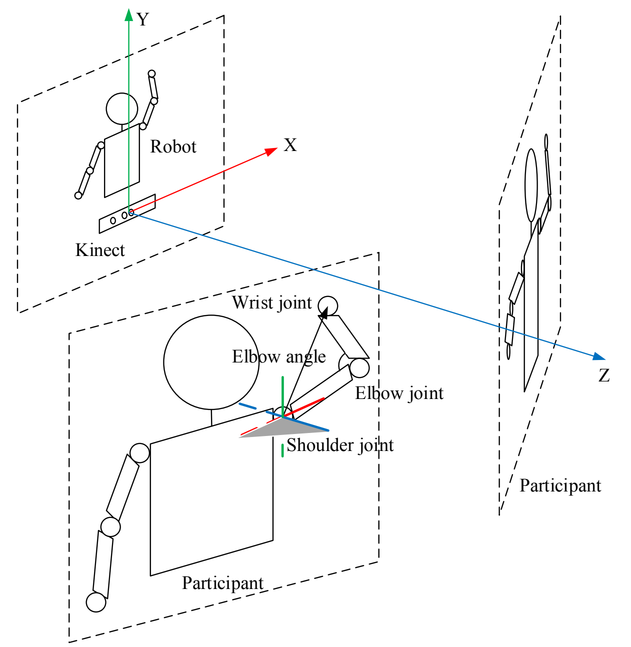

Figure 3. Relative positions of the robot and the participants in the Kinect coordinate space.

"Simon says" command. We used an existing Unity (unity3d.com) project to read button inputs from the Razer Hydra and created a socket which sent the values of the left and right controllers' trigger buttons to the user input detection program upon requests. If RAMU was interacting with one of the participants, the user input detection program returned true if the trigger button was clicked by that participant or false if it was not clicked at the end of a given detection time period. If both the participants were involved in the interaction, the user input detection program returned true only if the trigger buttons for both participants were clicked within the detection period.

Fig. 4 shows an example of the GUI. Both the color image view and the Kinect skeleton view were displayed to the administrator. The two skeletons were randomly ordered each time Kinect was turned on. In order to obtain the order of the skeletons, we extracted the head joint positions of the first skeleton, transformed it to the head joint positions on the color image view, and superimposed a cartoon head on the color image view. In the case that the person to the robot's

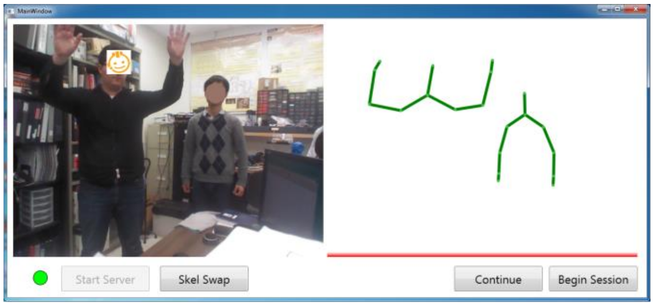

Figure 4. Graphical user interface.

right contributed to the first skeleton, we swap the order of the skeletons before starting the HRI. The green dot at the lower left corner of the GUI indicates that socket communication has been established.

C. *Supervisory Controller*

The Supervisory Controller module was implemented as a reactive system, which reacted to the events from the Sensing module and provided inputs to the Motion proxy and the TextToSpeech proxy. The robot's behaviors and the states of the Simon Says activity were adapted in real-time based on human interactions. Fig. 5 illustrates a flowchart that represents the control logic of robot playing the leader role. In this case, RAMU provided feedbacks based on the arm movements of both participants.

III. EXPERIMENT AND RESULTS

A. *Experiment Description*

We tested the system with four pairs of older adults in the laboratory setting. Table II shows the information of all the participants. The mini-mental state examination (MMSE) was used as a quantitative screening test for cognitive impairment [21]. MMSE score ranges from 0 (severe impairment) to 30 (no discernable impairment). Typically, a MMSE score below 24 starts to indicate possibility of dementia. The experimental protocol has been approved by the Vanderbilt University's Institutional Review Board. Each participant completed a survey instrument before and immediately after interacting with the system. During the HRI, participants sat side by side facing towards the NAO robot and the Kinect sensor. The relative positions of the robot and the participants are shown in Fig. 6. The interaction started off with introductions. NAO introduced itself and then asked the names of the participants. If any of the participants did not reply, NAO then turned to the other participant and asked him/her to help find out the name. Next, NAO explained the rules of the Simon Says activity and played the leader role (Fig. 5). When NAO finished, it asked one participant to be the leader. If the participant pressed the trigger button which indicated the "Simon says" statement, NAO would copy his/her arm movements for five seconds. After both the participants played the leader role, NAO asked them to smile and wave goodbye preceded by "Simon says" and the interaction ended. In the case that none of the participants was willing to play the leader role, NAO would be the leader again before ending the interaction. A research assistant administrated the interaction from an adjacent room equipped with a one-way mirror. In addition to the GUI, video recordings of both participants and the robot were displayed for the research assistant. The entire session took

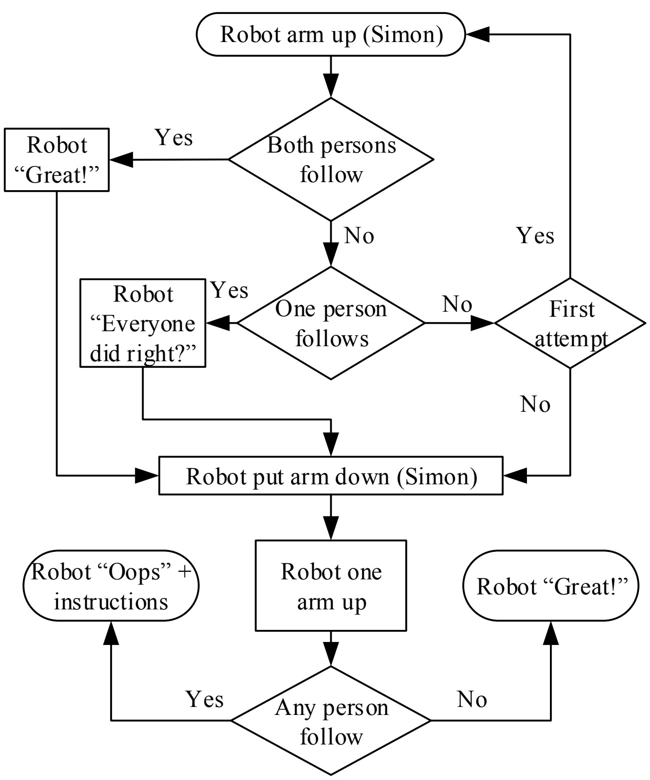

Figure 5. Flowchart of the robot plays the leader role.

TABLE II. PARTICIPANT DATA

Pair ID	Participant ID	Age	Gender	MMSE score
Pair 1	P01	86	Male	21
	P02	86	Female	28
Pair 2	P03	81	Male	29
	P04	83	Female	30
Pair 3	P05	82	Female	30
	P06	85	Male	29
Pair 4	P07	77	Female	29
	P08	70	Female	27

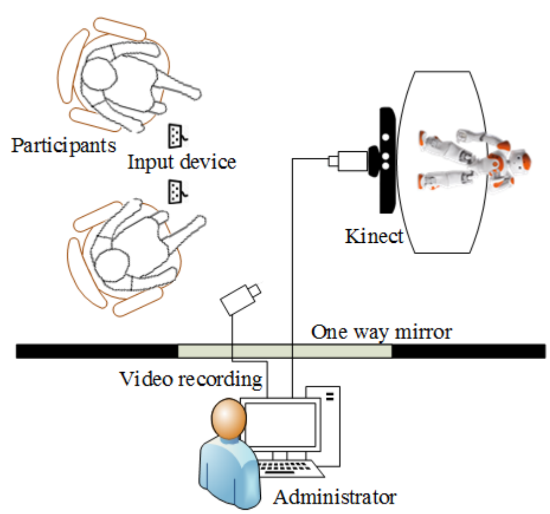

Figure 6. Experimental setup diagram.

approximately 30 minutes.

The survey instrument collected participants' perceptions on interacting with the robot, for example, "I would follow the advice the robot gives me"; and their perceptions on interacting with another person, e.g., "I would enjoy doing activities with another person". We also recorded their opinions on robot's appearance, whether the interaction was engaging, and suggestions to improve the system at the end of the HRI. All the ratings were based on a 7-point scale with lower score as being more positive.

B. Results

All eight participants finished the interaction without interruption. The skeleton order was correctly chosen by the system and it detected the gestures and button inputs without error. The use of the Razer Hydra to provide direct inputs is not very intuitive at first. In the beginning of the HRI, some participants forgot to press the trigger button after their response. In the future, we will introduce a practice HRI session before the Simon Says activity to familiarize the participants with the input device as well as the speech of the robot. Older adults' perceptions on interacting with the robot were more positive after the interaction as listed in Table III. Due to the small sample size ($N = 8$), none of the positive changes were statistically significant at the 0.05 level based on the two-tailed Wilcoxon Signed-Ranks Tests. Nonetheless, there were moderate effect size ($r \in [0.3, 0.5]$) for six out of the ten items (Table III). We are continuing our recruitment of older adults with and without cognitive impairment to participate in this study.

TABLE III. SURVEY RESULTS

Survey questions (robot)	**Mdn(Range)[a]**		**Z**	**p**	**r**
	Pre	**Post**			
I would enjoy a robot talking to me.	1(5)	1(0)	1.60	0.25	**0.40**
I would consider the robot a pleasant conversational partner.	3.5(5)	1.5(4)	1.63	0.19	**0.41**
I think a robot could be useful to me.	3(6)	2.5(6)	0.74	0.53	0.19
I would trust the robot to give me good advice.	4(6)	2.5(6)	0.97	0.44	0.24
I would enjoy doing things with a robot.	2(5)	1.5(4)	0.86	0.47	0.22
I would find a robot easy to use.	3(6)	1.5(2)	1.71	0.11	**0.43**
I would find the robot pleasant to interact with.	2.5(5)	1(4)	1.16	0.28	0.29
I would follow the advice the robot gives me.	4(6)	2(5)	1.81	0.13	**0.45**
I would find the robot enjoyable.	1.5(6)	1(1)	1.60	0.25	**0.40**
I would feel like the robot understands me.	3(6)	2(6)	2.00	0.08	**0.50**
Survey questions (peer)	**Pre**	**Post**	**Z**	**p**	**r**
I would enjoy doing activities with another person.	2(1)	1(2)	--	--	--
I would feel comfortable talking to another person.	1(0)	1(0)	--	--	--
I would help another person when needed.	1(0)	1(1)	--	--	--
I would accept help from another person.	1(0)	1(1)	--	--	--

a. Smaller values are more positive.

We also looked at individual's perception on the system and participants' self-rating scores on each individual item. After the HRI, P01 rated five items more negative; P02, P04, and P07 rated one item, two items, and three items more negative, respectively. The rest of the participants rated all the items more positive or the same as the pre- rating scores. For each individual item, at most two older adults rated the item more negative. None of the older adults' found the robot less enjoyable (item one and nine) after the HRI. Six out of the eight participants were provided with the survey questions about their perceptions on interacting with another person. Only P03 gave higher rating scores (more negative) for three of the four items. Although the post- survey did not imply any positive change, the scores are very low which indicates that participants enjoyed interacting with each other. In addition, we observed human-human interaction during the HRI from the video recordings. After the HRI, participants agreed that the appearance of the robot was pleasant (mean = 1.5, standard deviation = 0.93) and the interaction was engaging (mean = 1.25, standard deviation = 0.46).

C. Discussion

The success of robot-mediated human-to-human social interaction hinges upon: 1) older adults' acceptability and engagement in the HRI, and 2) system's capability to dynamically adapt based on perceived human interactions. RAMU was able to recognize the arm gestures and button inputs from both older adults and adapt its behavior in real-time. The preliminary results indicated that participants were positive and engaged in the interaction. We will expand the complexity of RAMU by incorporating more tasks to mediate human-to-human interaction and developing additional sensing components.

The Razer Hydra device used in this experiment requires some cognitive effort to get used to. A practice HRI session is likely to alleviate or remove this cognitive effort for older adults with and without mild cognitive impairment. However, for those who suffer from a severe cognitive impairment and are not able to use the device, we will explore alternatives for a smooth HRI for future studies. Speech recognition could be used to detect structured speech from each older adult. As the ultimate goal is to mediate human-to-human interaction, the robot could take advantage of other perception data such as word count and older adults' head orientations to infer their intentions, determine the amount of social interaction between older adults, and adapt system behavior accordingly.

IV. CONCLUSION

In this paper, we presented a novel robotic coach architecture, RAMU, which played Simon Says activity with a pair of older adults. Note that RAMU is not limited to Simon Says activity – many other interactive tasks can be easily incorporated within the architecture. We conducted a preliminary study with eight older adults with and without mild cognitive impairment to test the system functionality, explore whether older adults would engage in multi-user HRI, and obtain feedback to guide the refinement of RAMU. The system worked as desired and there was no dropout during the HRI. The button input device was not natural to use in the beginning but all the participants got used to it after a few attempts. No statistically significant results can be derived from the survey data due to the small sample size. In general, participants' perceptions on interacting with the system were more positive after the interaction. Their rating scores on interacting with another person were low representing positive opinions.

There are some limitations of this work we intend to address in the future. First, even though the current task design could involve multiple older adults, the task was not tailored to build up social communication and interaction between older adults. In the current system, social interaction between older adults were mostly observed when robot instructed them to interact with each other and when they were playing the leader role. In the future, we will modify the task design to reinforce social interaction between older adults. Second, participants were exposed to the system only once. In order to explore the efficacy of RAMU, we intend to conduct a longitudinal study with a larger number of older adults. Third, we intend to add objective measures to gauge social interaction during the HRI. We tested the system with pairs of older adults but it could be used for interaction between older adults and their family and caregivers as well. Despite these limitations, RAMU is among the first such architecture that we know of that could autonomously interact with more than one older adults simultaneously. Feedbacks from the participants were encouraging and we believe that such multi-user HRI will be beneficial in fostering human-to-human interaction in the future.

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