Assistive Robotics for Healthcare and Rehabilitation

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Abstract: The world's population is growing older, and therefore a wide array of new challenges is arising. Most of the ageing population is expected to need physical and cognitive assistance. As the elderly population continues to grow, a lot of research started to be dedicated to assistive systems aimed at promoting ageing-in-place, facilitating living independently in one's own home as long as possible, and helping caregivers and doctors to provide long-term rehabilitation/therapy protocols. In this paper, a new robotic system capable of providing motivational and encouragement cues to their users through social behavior is presented.

1. INTRODUCTION

The recent trend in robotics is to develop a new generation of robots that are capable of moving and acting in human-centered environments, interacting with people, and participating in our daily lives. This has introduced the need for building robotic systems able to learn how to use their bodies to communicate and to react to their users in a social and engaging way. Social robots that interact with humans have thus become an important focus of robotics research.

Research into Human-Robot Interaction (HRI) for *socially assistive* applications is in its infancy. Socially assistive robotics is an interdisciplinary and increasingly popular research area that brings together a broad spectrum of research including robotics, medicine, social and cognitive sciences, and neuroscience, among others. New applications for robots in health and education are being developed for different populations of users.

The world's population is growing older, and therefore a wide array of new challenges is arising. It is estimated that in 2050 there will be three times more people over the age 85 than there are today. Most of the ageing population is expected to need physical and cognitive assistance. As the elderly population continues to grow, a lot of research started to be dedicated to assistive systems aimed at promoting ageing-in-place, facilitating living independently in one's own home as long as possible, and helping caregivers and doctors to provide long-term rehabilitation protocols. The first efforts towards having socially assistive robotic systems for the elderly have been focused towards constructing robot-pet companions aimed at reducing stress and depression (Fong et. al 2003; Walton 2003).

In addition to the growing elderly population, other large user populations represent ideal beneficiaries of socially interactive assistive robotics. Those include individuals with physical impairments and those in rehabilitation therapy, where socially assistive technology can serve to improve not only mobility (Yanco 1998) but also for outcomes in recovery.

Finally, individuals with cognitive disabilities and developmental and social disorders (e.g., autism (Dautenhahn et. al. 2002)) constitute another growing population that could benefit from assistive robotics in the context of special education, therapy, and training.

In order to be able to aid the target user populations, an effective socially interactive assistive robot must understand and interact with its environment, exhibit social behavior, and focus its attention and communication on the user in order to help the user achieve specific goals. Social behavior plays an important role in the assistance of people with special needs. An adaptive, reliable and user-friendly *hands-off therapist robot* can provide an engaging and motivating customized therapy protocol to participants in laboratory, clinic, and ultimately, home environments, and can establish a very complex and complete human-robot relationship. Therefore, such robots must be endowed with human-oriented interaction skills and capabilities to learn from us or to teach us, as well as to communicate with us and understand us.

This paper presents different robotic systems designed for helping stroke patients and people suffering of age related cognitive impairments (i.e., dementia and/or Alzheimer's). The rest of the paper is structured as follows: Section 2 is dedicated to the description of the related work. Section 3 describes the learning and adaptation algorithms developed so as to provide multi-sessions customizable therapy protocol. Section 4 illustrates the robotic test-bed and Section 5 presents the experimental designs for stroke and dementia participants. Section 6 depicts the experimental results. And Finally Section 6 concludes this work.

2. BACKGROUND AND RELATED WORK

Two of the main problems encountered in the elder population are the Alzheimer's disease which is a form of dementia and stroke. Stroke is the leading cause of serious, long-term disability among American and European adults and the third leading cause of death in the United States (American Heart Association 2003). Each year over 730,000 American people and one million of people from 22 European countries suffer a stroke, and nearly 400,000 survive with some form of neurologic disability placing a tremendous burden on both the private and public health resources of the nation. Of all impairments that result from stroke, one of the most in need of effective rehabilitation studies is hemiparesis of the upper limb. Stroke patients with hemiparesis or hemiplegia (one-sided deficit) may have difficulty with everyday movement activities. This loss of function, termed "learned disuse", can improve with rehabilitation therapy during the critical post-stroke period. One of the most important elements of any rehabilitation program is carefully directed, well-focused and repetitive practice of exercises, which can be passive and active. In passive exercises, also known as hands-on rehabilitation, the therapist (or the robot) actively helps the patient to repeatedly move a limb as prescribed. In contrast, active exercises are performed by the patient him/herself, with no physical hands-on assistance. The vast majority of existing work into rehabilitation robotics focuses on hands-on robotic systems (e.g., (Brewer et al. 2003; Burgar et al. 2000; Reinkensmeyer et al. 2000)). However, recent results from physical therapy research show that such therapy may not be the most effective means of recovery from stroke, and are certainly not the only necessary type of much-needed treatment (Tapus et al. 2008).

Moreover, American Alzheimer's Association reported that more than one million residents in assisted living residences and nursing homes have some form of dementia or cognitive impairment and that number is increasing every day (American Alzheimer Association 2007). The rapidly increasing number of people suffering from Alzheimer's disease could cripple healthcare services in the next few decades. The latest estimate is that 26.6 million people were suffering from Alzheimer's disease worldwide in 2006, and it will rise to 100 million by 2050 — 1 in 85 of the total population. More than 40% of those cases will be in late-stage Alzheimer's, requiring a high level of attention equivalent to nursing home care. Dementia is a progressive brain dysfunction that affects the global functioning of the individual progressively impairing cognition (e.g., impaired memory and orientation, limitations of concentration, speech and hearing disorders), and changing personality and behavior. In our society of longer lifetime, the probability of suffering from dementia increases with advancing age. Dementia appears in the second half of the life, usually after the age of 65. The frequency of dementia increases with age, therefore from 2% at 65-69-year-olds to more than 20% at 85-89-year-olds. Thus, individuals suffering from moderate or severe dementia are restricted in their daily activities and in most cases need for special care. As with numerous other diseases there is no cure for dementia but medication and special therapy can improve disease symptoms. Non pharmacological treatments focus on physical, emotional and also mental activation. Engagement in activities is one of the key elements of good dementia care. Activities (e.g., music therapy, arts and crafts) help individuals with dementia and cognitive impairment maintain their functional abilities and can enhance quality of life. Also cognitive rehabilitation therapies that focus on recovering and/or maintaining cognitive abilities such as memory, orientation, and communication skills are other specific therapeutic protocols designed for individuals with dementia. Finally, physical rehabilitation therapies that focus on motor activities help individuals with dementia rehabilitate damaged functions or maintain their current motor abilities so as to keep the greater possible extent of autonomy. Very few researches have been done in the area of therapeutic robots for individuals suffering from dementia and cognitive impairment. Libin and Cohen-Mansfield (Libin, Cohen- Mansfield 2004) describe a preliminary study which compares the benefits of a robotic cat and a plush toy cat as interventions for elderly persons with dementia. Furthermore, Kidd, Taggart, and Turkle (Kidd, Taggart et al. 2006) use Paro seal robot to explore the role of the robot in the improvement of conversation and interaction in a group. Finally, Marti, Giusti, and Bacigalupo (Marti, Giusti et al. 2007) justify a non-pharmacological therapeutic approach to the treatment of dementia that focuses on social context, motivation, and engagement by encouraging and facilitating non-verbal communication during the therapeutic intervention.

The work proposed here, involves an autonomous robot providing contact-free rehabilitation monitoring, assistance, and encouragement to users (usually vulnerable populations), while also being capable of providing detailed reports of patient progress to physicians and therapists. The main advantages of the proposed approach are in providing time-extended personalized exercise supervision and encouragement while saving therapist time. By focusing on non-contact strategies, a vast majority of the complex issues of safety that pose inherent challenges in hands-on robot-assisted rehabilitation can be avoided.

Hence, the work proposed here will focus on robot behavior adaptation to user's personality, preferences and disability level, aiming toward a customized therapy protocol for stroke rehabilitation and other elderly specific application domains.

3. ROBOT LEARNING AND BEHAVIOR ADAPTATION

1) Robot Learning and Behavior Adaptation to User Personality and Preferences

The main goal of this first methodology is to develop a robot behavior adaptation system that allows optimizing on the fly three main interactional parameters (interaction distance/proxemics, speed, and vocal content) so as to adapt it to the user's personality and thus improve the user's task performance. These parameters define the behavior (and thus personality) of the therapist robot. Task performance is measured as the number of exercises performed in a given period of time; the learning system changes the robot's personality, expressed through the robot's behavior, in an attempt to maximize the task performance metric.

A new learning algorithm has been developed. This approach is based on the *policy gradient reinforcement learning (PGRL)* and consists of the following steps:

(a) parametrization of the behavior – initial policy π;

(b) approximation of the gradient of the reward function in the parameter space;

$$\pi_{i+1} = \pi_i + \eta \frac{\partial \hat{\rho}}{\partial \pi} \qquad (1)$$

(c) movement towards a local optimum.

The reward function is monitored to prevent it from falling under a given threshold, which would indicate that the robot's current behavior does not provide the patient with an ideal recovery scenario. This triggers the activation of the PGRL adaptive algorithm phase to adapt the behavior of the robot to the continually-changing factors that determine the efficiency of the recovery process.

More details about this work can be found in (Tapus et al. 2008).

2) Robot Learning and Behavior Adaptation to User Disability

The second learning and robot behaviour adaptation methodology was designed for the interaction between the robot and people suffering of dementia and/or Alzheimer's with the main goal of helping these individuals to improve or maintain their cognitive attention through encouragements in a specific music based cognitive game.

This approach consists of two parts: supervised learning and adaptation.

The supervised learning system learns for each game level and for each disability bucket (mild, moderate, and severe) an *Accepted Variation Band (AVB)* as a function of users' task performance to the cognitive game and the correctness of their answers.

The learning phase is followed by an adaptation phase where the robot adapts its behavior so as to minimize reaction time and maximize user correct answers.

4. EXPERIMENTAL PLATFORM

In this work, a humanoid torso mounted on a Pioneer mobile platform (Figure 1) has been used. The robot base used is an ActivMedia Pioneer 2DX equipped with a speaker, a Sony Pan-Tilt-Zoom (PTZ) color camera, and a SICK LMS200 eye-safe laser range finder. The biomimetic anthropomorphic version of the setup involves a humanoid torso, mounted on the same mobile base (Figure 1), and consisting of 22 controllable degrees of freedom, which include: 6 DOF arms (x2), 1 DOF gripping hands (x2), 2 DOF pan/tilt neck, 2 DOF pan/tilt waist, 1 DOF expressive eyebrows, and a 3 DOF expressive mouth. All actuators are servos allowing for gradual control of the physical and facial expressions.

Fig 1. Human-like torso mounted on the mobile base

5. EXPERIMENTAL DESIGN

1) Experiment designed for post-stroke participants

The experiment designed for stroke population consists of testing the adaptability of the robot's behavior to the participant's personality. In the experiment, the human participant stands and faces the robot. The experimental task is a common object transfer task used in post-stroke rehabilitation and consisted of moving pencils from one bin on the left side of the participant to another bin on his/her right side. The bin on the right was on an electronic scale in order to measure the user's task performance. The system monitored the number of exercises performed by the user. The participants were asked to perform the task for 15 minutes, but they could stop the experiments at any time. At the end of each experiment, the experimenter presented a short debriefing. Before starting the experiments, the participants were asked to complete two questionnaires: (1) a general introductory questionnaire in which personal details such as gender, age, occupation, and educational background were determined and (2) a personality questionnaire based on the Eysenck Personality Inventory (EPI) for establishing the user's personality traits.

The robot used the algorithm described in Section 3 to adapt its behavior to match each participant's preferences in terms of therapy style, interaction distance, and movement speed.

The learning algorithm was initialized with parameter values that were in the vicinity of what was thought to be acceptable for both extroverted and introverted individuals, based on the user-robot personality matching study described in (Tapus and Mataric 2006).

The PGRL algorithm used in this experiment evaluated the performance of each policy over a period of 60 seconds. The reward function, which counted the number of exercises performed by the user in the last 15 seconds was computed every second and the results over the 60 seconds "steady" period were averaged to provide the final evaluation for each policy.

The threshold for the reward function that triggered the adaptation phase of the algorithm was adjusted to account for the fatigue incurred by the participant. The threshold and the time ranges are all customizable parameters in the algorithm developed in this paper.

In the post-experiment survey, the participants were asked to provide their preferences related to the therapy styles or robot's vocal cues, interaction distances, and robot's speed from the values used in the experiments.

Four different scenarios were designed for both extroverted and introverted personality types: the therapy styles ranged from coach-like therapy to encouragement-based therapy for extroverted personality types and from supportive therapy to nurturing therapy for introverted personality types. The words and phrases for each of these scenarios were selected in concordance with encouragement language used by professional rehabilitation therapists. The coach-like therapy script was composed of strong and aggressive language (e.g., ”Move! Move!”, ”You can do more than that!”). Higher volume and faster speech rate were used in the pre-recorded transcript voice, based on the evidence that those cues are associated with high extroversion. The aggressiveness of words, the volume, and the speech rate diminished along with the robot's movement towards the nurturing therapy style of the interaction spectrum. The nurturing therapy script contained only empathetic, gentle, and comforting language (e.g., ”I'm glad you are working so well.”, ”I'm here for you.”, ”Please continue just like that”, ”I hope it's not too hard”). The voice used had lower volume and pitch. A set of 3 interaction distances and speeds were chosen for each introverted and extroverted personality type.

2) Experiment designed for cognitive impaired participants

The task designed for improving or maintaining the cognitive attention of individuals suffering of cognitive impairment consisted of a music game. The robot uses the following transcript: “We will play a new music game. In it, we will play a music collection of 4 songs. The songs are separated by silence. You will have to listen to the music and push the button corresponding to the name of the song being played. Press the button marked “SILENCE” during the silence period between the songs. The robot will encourage you to find the correct song.” (see Figure 2 and 3)

The first session is the orientation session. In it, the participant is ‘introduced’ to the robot. The humanoid robot is brought into the room with the participant, but is not be powered on. During this introduction period, the nurse/physical/music therapist will explain the robot behavior, the overall goals and plans of the study, and generally inform the participant of what to expect in future sessions.

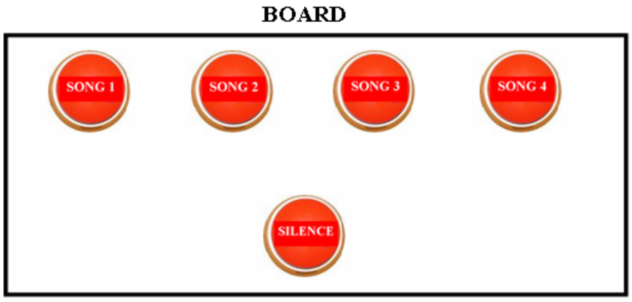

Fig 2. Cognitive Game: Name That Tune – Experimental Setup

Finally, at the end of the first session, the Standardized Mini-Mental State Examination (SMMSE) cognitive test is performed so as to determine the participant's level of cognitive impairment and the stage of dementia. This test provide information about the cognitive (e.g., memory recall) level of impairment of the participant for use in the interactions with the robot.

The primary purpose of the first session is to determine the participant's initial, no-robot condition motor task functionality, mental state, and level of cognitive impairment. The nurse/physical/music therapist and the experiment designers will analyze the mental state and level of cognitive impairment.

This experiment is designed to improve the participant's attention and consists of a cognitive game called Song Discovery or Name That Tune (i.e., find the right button for the song, press it, and say the name of the song). The criteria for participation (in addition to the Alzheimer's or dementia diagnosis) in this experiment include the ability to read large print and to press a button. The participant stands or sits in front of the experimental board fixed on a wall. On the board are mounted 5 large buttons (e.g., the Staples EASY buttons). Four buttons correspond to the different song excerpts (chosen as a function of user's preference) and the last button corresponds to the SILENCE or no song excerpt condition. Under each button, a label with the name of the song (or SILENCE) is printed.

The participants are first asked by the music therapist or the robot to read aloud the titles of the songs and to press a button. Some additional directions are given. They are also directed to press the SILENCE button when there is no music playing. After a review of the directions, the music collection is played.

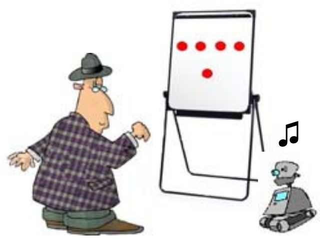

Fig 3. The condition tested: human-robot interaction

A piece of music compilation contains the different chosen song excerpts and the silence condition. The duration of the music compilation lasts in-between 10-20 minutes, as a function of user level of cognitive impairment. A song excerpt can be vocal, instrumental, or both. The order of song excerpts is random.

6. EXPERIMENTAL RESULTS

1) Experimental results for the post-stroke experiment

The subject pool consisted of 12 participants (7 male and 5 female). The participants ranged in age between 19 and 35, 27% were coming from a non-technological field, while 73% worked in a technology-related area.

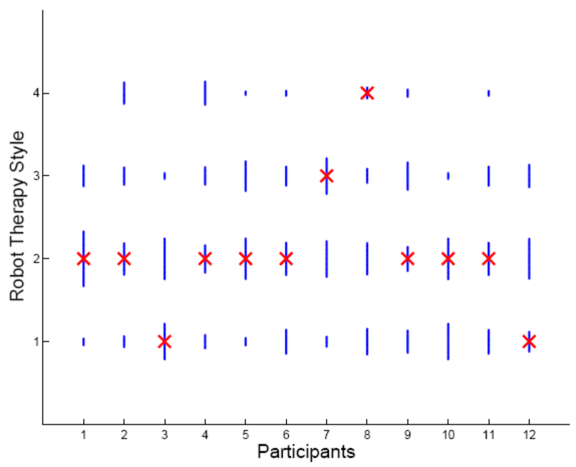

Fig 4: The percentage of time that the 12 participants interacted with each of the four therapy styles of the robot (for extroverted and introverted participants). The crosses represent the participants' preferences.

As shown in Figure 4, the robot adapted to match the preference of the participant in almost every single case. The only exception was the interaction with participant 8. Despite the fact that the time spent in the preferred training style of that participant was smaller than the time spent in other training styles, the robot converged to it at the end of the exercise period. The cause for this slight inconsistency was the fact that the initial state of the robot was in a training style that was furthest from the preference of the participant. The fact that only perturbations to neighboring training styles were allowed, combined with the relative short duration of the exercise contributed to this result.

Hence, the results obtained support our hypothesis that the robot could adapt its behavior to both introverted and extroverted participants.

2) Experimental results for the cognitive game experiment

The initial pilot experimental group consisted of 10 participants (5 male, 5 female), from the partner Silverado Senior Living (The Huntington, Alhambra, CA, USA) care facility. All the participants were seniors over 70 years old suffering of cognitive impairment and/or Alzheimer's disease. The cognitive scores given by the SMMSE test were the following: 2 mild; 1 moderate; and 7 severe. Due to the total unresponsiveness of 6 of the severe participants, only 1 severe participant was retained for the rest of the experiments, therefore having a final group composed of 4 participants.

The learning and adaptation results of the system are illustrated below in Figure 5 and Figure 6.

Outcomes were quantified by evaluating task performance and time on task. Caregivers were also asked about the improvements and the possibility of transfer of knowledge (interactive format with the patients, family members, and the robot).

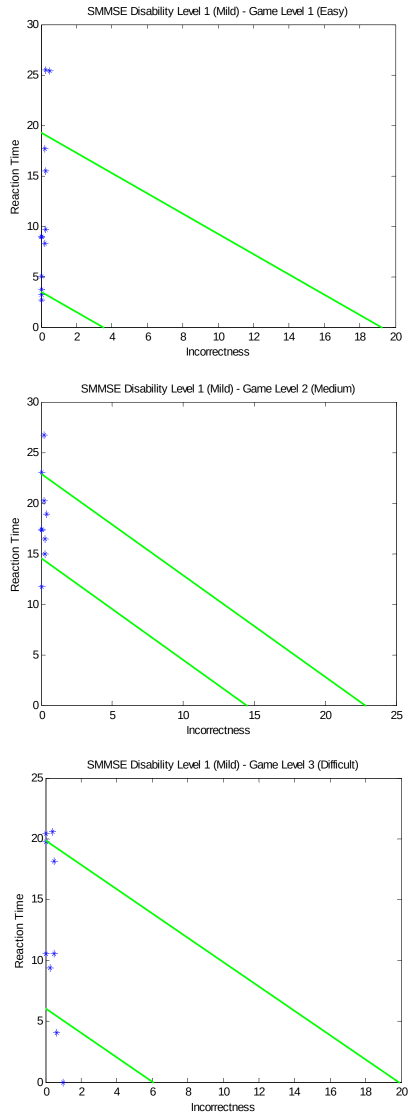

Fig 5: Learned *Accepted Variation Bands* for Mild disability level and all game levels: easy, medium, and difficult

The robot succeeded to adapt its behaviour as a function of the user cognitive impairment level so as to maximize user task performance and consequently user cognitive attention and memory recall.

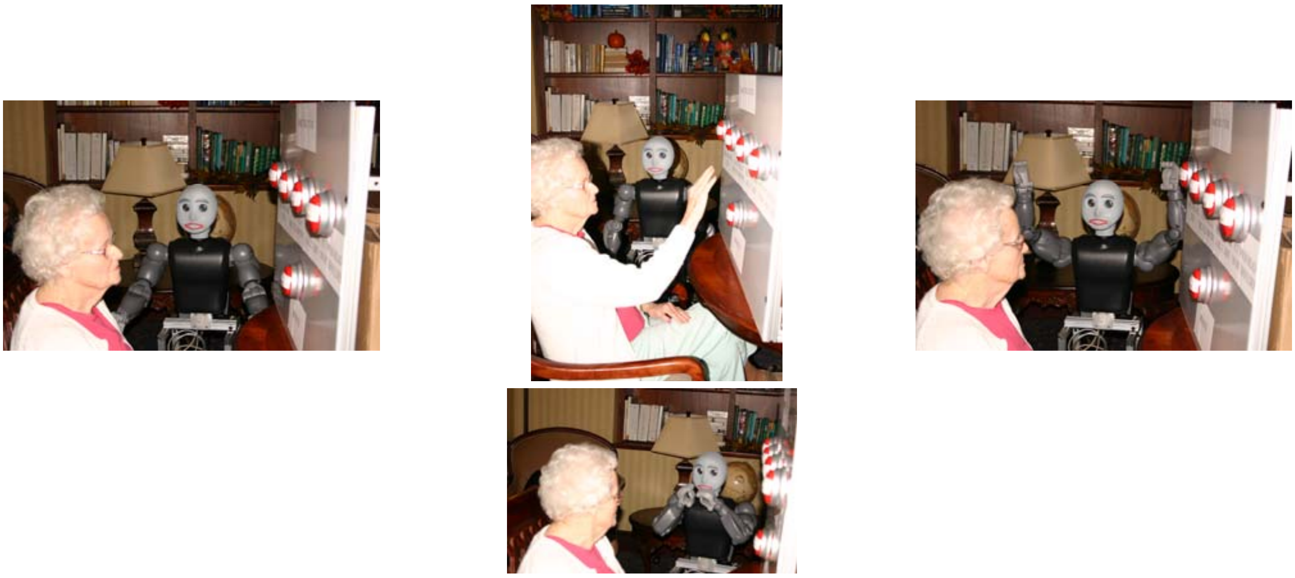

Fig 6: Human-User interacting with the robot during the actual music game: the robot is giving hints related to the music game, the user answers, and the robot congratulates and applauses the correct answer of the user

7. CONCLUSIONS

This research aims to develop a socially assistive therapist robot for post-stroke individuals and for individuals suffering from dementia and/or other cognitive impairment. The main goal of the robot is to improve through the social interaction their motor/cognitive abilities and therefore their quality of life. The assistive human-robot interaction model presented in this paper has been tested with a bio-mimetic robotic system with human users suffering from stroke and dementia. This model involves user engagement through speech and gesture. The preliminary results already show promise for our approach.

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