The Grand Challenges in Socially Assistive Robotics

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Within this article, the authors discuss the grand research and application challenges in socially assistive robotics.

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I. SOCIALLY ASSISTIVE ROBOTICS

SOCIALLY intelligent robotics is the pursuit of creating robots capable of exhibiting natural-appearing social qualities. Beyond the basic capabilities of moving and acting autonomously, the field has focused on the use of the robot's physical embodiment to communicate and interact with users in a social and engaging manner. One of its components, *socially assistive robotics*, focuses on helping human users through social rather than physical interaction [1]. The study of human-robot interaction (HRI) for socially assistive robotics applications is a new, 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.

In contrast to interactive robotics, which aims to entertain and/or create simple basic relationships with human users, assistive robotics focuses on aiding human users with special needs in their daily activities. Assistive robotics in general and socially assistive robotics in particular have the potential to enhance the quality of life for broad populations of users: the elderly, individuals with physical impairments and those in rehabilitation therapy, and individuals with cognitive disabilities and developmental and social disorders. However, such systems pose a new challenge of being both population-relevant and highly individualized to the special needs of each user in the particular beneficiary population.

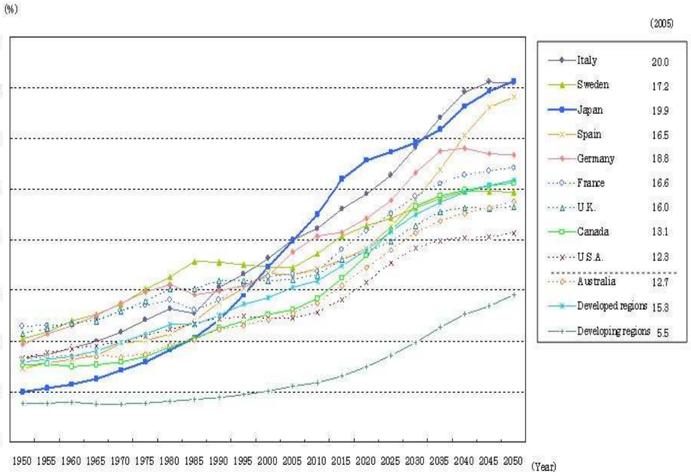

Fig. 1. Trends in Percentage of the Elderly in the World; source: UN, "World Population Prospects", The 2004 Revision; the data for Japan is based on "Population Census of Japan" (Ministry of Internal Affairs and Communications) and "Population Projection for Japan" (National Institute of Population and Social Security Research, January 2002).

II. APPLICATION DOMAINS

In this section we review the principle application domains of socially assistive robotics which have so far been identified: care of the elderly, care of individuals with physical recovery/rehabilitation and training needs, and care of individuals with cognitive and social disabilities.

A. Care of the Elderly

As the world's population is growing older, a wide array of new challenges are arising. It is estimated that in 2050 there will be three times more people over the age 85 than there are today (see Figure 1). A significant portion of the ageing population is expected to need physical and cognitive assistance. Yet, space and staff shortages at nursing homes and other care facilities are already an issue today. As the elderly population continues to grow, a great deal of attention and research will be dedicated to assistive systems aimed at promoting ageing-in-place, facilitating living independently in one's own home as long as possible. Assistive robotic systems for the elderly, therefore, require technologies capable of being commanded through natural communication (e.g., speech, gestures), of fetching items, and of assisting with daily activities (e.g., dressing, feeding, moving independently). In the context of socially assistive robotics, the first efforts have focused on robotic pets, companions that attempt to reduce

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stress and depression [2]. Companion robots are designed to fulfill some of the roles of pets but without the effort involved in animal care. Researchers have used robotic animal toys, such as a seal (i.e., PARO [2]), a cat [2], a dog (i.e., Sony AIBO) and a teddy bear (i.e., The Huggable from MIT) in order to attempt to improve physiological and psychological health in elderly patients. These studies have shown that elderly users smiled and laughed more, and became less hostile to their caretakers and more socially communicative. More generally, the research literature has demonstrated that the physiological health and emotional well-being of the elderly are ameliorated in contact with animals [3], [4].

B. Care of Individuals with Physical Recovery, Rehabilitation and Training Needs

Motivation is recognized as the most significant challenge in physical rehabilitation and training. Socially assistive robotics technology has the potential to provide novel means for monitoring, motivating, and coaching. Post-stroke rehabilitation is one of the largest potential application domains, since stroke is a dominant cause of severe disability in the growing ageing population. In the US alone, over 750,000 people suffer a new stroke each year (National Institute of Neurological Disorders and Stroke, January 2006), with the majority sustaining some permanent loss of movement. Stroke patients frequently have difficulty with everyday functional movements and activities; the loss of function can be decreased through rehabilitation therapy during the critical post-stroke period. Such rehabilitation therapy involves carefully designed repetitive exercises, which can be passive and active. In passive exercises, the therapist (or a robot) actively helps the patient to repeatedly move the stroke-affected limb as prescribed. In active exercises, the patient does the work him/herself, with no physical assistance.

The majority of rehabilitation robotics research to date has focused on passive post-stroke exercises (e.g., [5]). Socially assistive robotics, however, provides a means of addressing active rehabilitation exercises. Eriksson and Matarić [6] demonstrated a hands-off therapist robot that assists, encourages, and socially interacts with patients, shown in Figure 2. The shared physical context and physical movement of the robot, encouragement, and continuous monitoring were shown to play key roles in stroke patient compliance with rehabilitation exercises. Continuing work has studied key aspects of embodied human-robot interaction ([1], [7]) as well as the role of human and robot personality ([8]), aiming toward establishing a “ common ground” between the human user and the robot and which permitting a natural, nuanced, and engaging interaction.

A variety of other real-world domains feature repetitive exercises that require sustained motivation. For example, Kang and Matarić [9] demonstrated a therapist robot which monitors and encourages a cardiac patient during breathing (spirometry) exercises (see Figure 3).

C. Care of Individuals with Cognitive Disabilities

Individuals with cognitive disabilities and developmental and social disorders constitute another growing population that may benefit from assistive robotics in the contexts of special education, therapy, and training. Most of the socially assistive research to date in this area has focused on Autism Spectrum Disorder (ASD). Current research suggests that 1 in every 300 children will be diagnosed with ASD; studies have found prevalence rates that vary between 1 in every 500 to 1 in every 166. Furthermore, the rate of diagnosis increased six-fold between 1994 and 2003. The cause of the increase is not yet known; however, early intervention is critical to enabling a positive long-term outcome, and even with early intervention, many individuals will need high levels of support and care throughout their lives (Department of Health and Human Services, Centers for Disease Control and Prevention: Developmental Disabilities: Autism Information Center, January 2006).

A number of research groups have examined the response of children with autism to robots [10], [11]. Each of these studies has demonstrated that robots generate a high degree of motivation and engagement in subjects, including subjects who are unlikely or unwilling to interact socially with human therapists. This presents the hope that a robot might be used as a ”social crutch” which engages children, teaches them social skills incrementally, and assists in the transfer of this knowledge to interactions with humans. However, the design criteria

Fig. 2. Therapist robot encouraging and monitoring stroke patient during the rehabilitation therapy (work done at USC [6])

Fig. 3. Clara the therapist robot assisting a subject with the spirometry exercise (work done at USC [9])

for what makes individuals with autism likely to respond to these devices are not understood. The robots used in these studies include four-wheeled rovers [10], anthropomorphic robotic dolls (e.g., ROBOTA - EPFL, Switzerland), a spherical robot ball with eyes [11], and an expressive snowman-like device (e.g., Keepon - NICT, Japan). These robots show a wide range of anthropomorphic characteristics, behavioral repertoires, aesthetics, and sensory and interactive capabilities. While there are many studies of the effects of these interaction variables on typical adults, very little is known about how individuals with autism respond to these design dimensions. While we have many expectations for why children with autism respond so positively to these robots, we have no direct experimental data that provide an analysis of the design criteria that are important to producing this response.

Scassellati has identified a range of possible areas in which social robotics technology may help to diagnose, treat, and understand autistic spectrum disorders [12]. One of the most promising areas is in the quantification and diagnosis of the disorder. To date, autism remains a behaviorally specified disorder; there is no blood test, no genetic screening, and no functional imaging test for its diagnosis. Instead, diagnosis relies on the clinician's intuitive feel for the child's social skills including eye-to-eye gaze, facial expression, body postures, and gestures. These observational judgments are then quantified according to standardized protocols that are both imprecise and subjective (e.g., [13]). The broad disagreement of clinicians on individual diagnoses creates difficulties both for selecting appropriate treatment for individuals and for reporting the results of population-based studies [14]. Assistive robots offer a unique opportunity for quantifying social behavior. Because these systems are designed to detect, measure, and respond to social behavior, they offer a repeatable, objective, and quantitative description of the social responses of an individual that is relatively free of observer bias. Ongoing work focuses on whether or not the information gathered from these systems is a useful diagnostic instrument [12].

The above-listed three application domains constitute the largest beneficiary populations relevant to socially assistive robotics today, but it is expected that other uses and benefits of the technology will continue to emerge as the field grows.

III. FOCI OF STUDY IN SOCIALLY ASSISTIVE ROBOTICS

Social behavior plays a fundamental role in assisting all people, including people with special needs. The robot's physical embodiment, its physical presence and appearance, and its shared context with the user, are fundamental for creating a time-extended engaging relationship with the user. We posit that an adaptive, reliable and user-friendly hands-off robot that can provide an engaging and motivating customized therapy protocol to participants in school, clinic, and ultimately, home environments, can establish a very complex and complete human-robot relationship. To make this possible, such robots must be endowed with human-oriented interaction skills and capabilities, exhibit context and user-appropriate social behavior, and focus attention and communication on the user in order to help the user achieve specific goals.

We propose to organize the challenges of socially assistive robotics around six broad, and naturally inter-related, research topics: embodiment, personality, empathy, engagement, adaptation, and transfer. We briefly discuss each in turn.

A. Embodiment

The robot's physical embodiment plays a key role in its assistive effectiveness. Embodiment denotes not only physical reality but also participative status. We focus on embodied interaction, because the physical and social world yields form, substance, and meaning from such interaction. The notion of embodiment represents a strong concept in the phenomenology of perception developed by Maurice Merleau-Ponty [15]. Three different meanings of embodiment are identified in that work:

- The physical embodiment of a human subject, with legs and arms, and of a certain size and shape;
- The set of bodily skills and situational responses that humans have developed;
- The cultural skills abilities and understandings that humans responsively gain from the cultural world in which they are embedded.

All three of the above aspects must be considered when creating an embodied robotic system. Nevertheless, it is well established that people attribute intentions, goals, emotions, and personalities to even the simplest of machines with life-like movement or form [16]. Because of this combination of properties, embodiment constitutes a key means of establishing human-robot interaction and user engagement. First efforts in this area have already been made (e.g., [17], [18]).

B. Personality

Personality is a key determinant in human social interactions. Research has shown a direct relationship between personality and behavior [19], [6]. To the personality psychologist, the behaviors of greatest importance are those that are:

- Relatively pervasive in the person's life-style in that they show some consistency across situations;
- Relatively stable in the person's life-style across time;
- Indicative of the uniqueness of the person.

Consequently, personality is also a key factor in human-robot interactions (HRI) [20]. With a view of having robots as companion and assistant of humans, we are motivated towards developing the robot personality along the lines of what we know about us. It has been argued that robot personality should match that of the human user [20]. While there is no generic definition of personality, one definition, based on the literature, defines personality as the pattern of collective character, behavioral, temperamental, emotional and mental traits of an individual that have consistency over time and situations.

To date, little research into human-robot personality matching has been performed. The first efforts towards investigating the role of the robot's personality in the hands-off therapy process, by Tapus and Matarić, focused on the relationship between the level of extroversion-introversion of the robot and the user [8].

C. *Empathy*

Empathy is a provocative construct, evoking debate over its measurement in any context, and its potential applications in robotics. It is particularly relevant to socially assistive robotics, because it is known to play a key role in patient-centered therapy; it implies the apprehension of another's inner world and a joint understanding of emotions.

Empathy is important in therapeutic improvement (e.g., [21]) and their assumption that empathy mediates pro-social behavior. Rogers [21] showed that patients who have received empathy, genuineness, and unconditional positive regard from their therapist recovered faster. Therefore, we posit that empathy can ameliorate patient satisfaction and motivation to get better, and enhance adherence to therapy programs in the context of patient-therapist interaction.

Machines cannot feel empathy. However, it is possible to create robots that display overt signs of empathy. In order to emulate empathy, a robotic system should be capable of recognizing the user's emotional state, communicating with people, displaying emotion, and conveying the ability of taking perspective. It should appear as if it understands others' emotions, can mimic those emotions, and can behave as if the others' emotions affect it. People experience emotions and express those emotions to communicate to others. We posit that the understanding and exchanges of emotional expressions between people and machines will reinforce the formation of the desired assistive relationships we outlined above.

D. *Engagement*

Engagement is an important element in socially assistive robotics, referring to the establishment and maintenance of a collaborative connection between the human user and the robot. Assuming human-human interactions as a baseline, to engage in social interactions, a robot must be aware of human presence and able to understand when humans want to interact. Also, to have a natural interaction, the robot must be able to take initiative by drawing attention to itself. These can be achieved either by maintaining persistent eye contact or by fixating gaze on the user while maintaining a certain distance that can facilitate social interaction. Both verbal and non-verbal communication are also necessary so as to establish an engaging interaction. The robot should be able to communicate with the user through both verbal and non-verbal channels; for example, while the user is speaking, the robot should appear engaged or disengaged in the conversation and should nod in approval or express disapproval. Work with simple agents and robots that have addressed engagement includes [22] and [23].

E. *Adaptation*

Learning to communicate and adapt our behavior to the information we receive have been fundamental to human evolution. To provide robots with sophisticated capabilities similar to those embedded in humans has proven to be a very difficult task. In the socially assistive robotics context, learning needs to focus both on the short-term changes that represent individual differences and on the long-term changes that allow the interaction to continue to be engaging over a period of months and even years. The robot should be able to learn from the user and adapt its capabilities to the user's personality, moods, and preferences so as to provide a customized interaction. Very few research works are addressing the learning through long-term social interaction. Various learning approaches for human-robot interaction have been proposed in the literature, but none include the user's profile, preferences, and/or personality. Since socially assistive robotics is dealing with vulnerable users, the robot must be capable of careful consideration of the user's needs and disabilities.

F. *Transfer*

In addition to crafting an interaction that is meaningful and engaging while the user is with the robot, one of the research goals for most socially assistive robots is to create long-term behavioral change. For example, we want a child with autism to not only practice and learn social skills while interacting with a robot but also to see these skills transfer to their interactions with peers and parents; we want robots that enhance and monitor physical therapy for stroke patients to have a lasting impact on the patient's ability and willingness to engage in physical therapy without the robot's prompting; we want the elderly individual who engages in social storytelling with a robot to also be more apt to engage friends and family. While we have some understanding of how to enhance skill transfer and behavioral change via human-human interactions, it is an open question how to best structure robot-human interaction to maximize the possibility of these transfer situations. In many ways, skill and behavior transfer is the ultimate metric of success for many types of socially assistive devices. The demonstration of this transfer requires longitudinal studies of individuals engaged in regular interactions with robotic systems. The technical challenges of long-term user studies with what are usually research prototype devices are both substantial and numerous.

IV. SOCIALLY ASSISTIVE ROBOTICS: GRAND CHALLENGES

It is clear that socially assistive robotics presents great potential uses and grand multi-faceted challenges. Here we attempt to summarize the latter.

A. *Research Challenges for Socially Assistive Robotics*

Numerous interesting questions and issues need to be addressed toward creating robust, reliable, user-friendly, empathetic, and encouraging socially assistive robotic systems, including: “What are the circumstances in which people (especially those with special needs) accept an assistive robot in their environment?”, “What modes of communication should be employed?”, “What is the role of the robots physical embodiment?”, “How do verbal and non-verbal interaction interact to facilitate engagement and transfer?”, “What is the role of empathy in socially assistive robotics and how can it be emulated?”, “How can we model the behavior and encouragement of the therapist robot as a function of the personality of

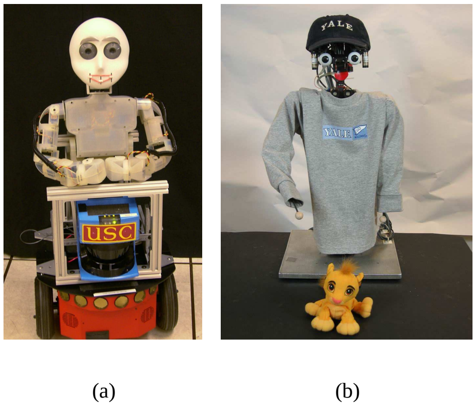

Fig. 4. Socially Assistive Robots: (a) Bandit, the hands-off therapist robot designed at University of Southern California / Interaction Lab; (b) Nico, an upper-torso humanoid designed to match the size of an average one-year-old infant, built at Yale University.

the user?”, “How can we integrate a priori knowledge about the user into the robotic system?”, “How can the interaction design ensure safety?”, “How can friendly and familiar interaction models be developed?”, “What relative roles do social and physical robot assistance play and how should they best be traded-off?”, “What types of control architectures are well suited?”, “How can the robot’s perception, competence, and awareness of the world be represented in a form accessible and understandable to non-technical users?”, “What models from psychology, cognitive science, and social science can be effectively utilized to help the goals of social assistive robotics?”.

As part of physical presence, the appearance of the robot is one of the important issues in human-robot interaction; it must be appropriately matched to the robot’s cognitive and interactive capabilities. The more human-like the robot appears, the higher the expectations of people interacting with it are. In socially assistive robotics, believability plays a more important role than realism. Hence, a child-like appearance or anthropomorphic but not highly realistic appearance is typically more suitable for assistive tasks. Our therapists robots, shown in Figure 4, are designed with this philosophy in mind.

Humans need to create strong bonds with robots of the nature similar to those formed with other humans, in order to have effective assistive therapists robots. An assistive robot must effectively interact with people it is serving, displaying natural communicative behavior that is not only acceptable but appealing to its users. Communication is a rich multi-modal process. The communication between the human and robot can be realized by using different means: a speech interface, a touch-screen, and natural human gesture. Verbal and non-verbal communication play a crucial role in socially assistive robotics and provide social cues that make the robots appear more “intuitive and natural”. We posit that understanding human affect and reacting to behave more suitably to different social situations (e.g., so as to avoid misunderstandings and to permit far more natural interactions) and to react to it appropriately, can help the robots improve the human-user task performance. Ideally, the robot should be capable of: (1) recognizing, understanding, and interpreting the user’s emotional state (emotional expression and/or reaction created by a specific situation); (2) processing and expressing its emotions by using different modalities (voice, facial expressions, and body movements and gestures); (3) communicating with others; and (4) perspective taking; in order to express personality and empathy. Social psychologists have also observed a strong relationship and synchrony between gestures, verbalization, and movement in everyday human social interactions. Therefore, we posit that the robot’s empathic state can be reinforced by appropriate verbal communication; the robot can express its understanding through empathetic tone of voice and phrases that are appropriately matched to the emotional state of the user. Recent research work in linguistics showed that a doctor’s empathetic voice encourages the patient to adhere to the treatment regime and helps to building doctor-patient trust. Hence, both language and “body language” are needed as HRI tools to express empathy.

Robots must maintain an appropriate spatial distance to people so as to respect their personal and social spaces. In order to engage in social interactions, the robot needs to be aware of human presence, detect the willingness of humans to interact, and determine and learn appropriate personal space ranges for various users. The 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. The different user groups’ responses, testing for age, gender, and domain differences should be evaluated.

The robot should adapt its behavior to user personality, user preferences, and user profile so as to provide an engaging and motivating customized therapy protocol. Importantly, the robots will always subordinate itself to the patient’s desires and preferences, thereby promoting patient-centered practice and avoiding the complex issues of taking control away from patients and dehumanizing health care

Methods for measuring the effectiveness of socially assistive robots also need to be developed. In a recent research work [24], Steinfeld, Fong et al. discuss the common metrics in human-robot interaction. They suggest that for measuring the effectiveness of social robots, the interaction style or social context, persuasiveness, trust, engagement, and compliance are the main factors for consideration. The field of socially assistive robotics is much too young to be amenable to benchmarking. Furthermore, because of its inherent focus on human-centered technology, it is difficult to see how benchmarks can be applied. For example, even if a methodology works on a group of children with autism, the same methodology may not give similar results on a different group of children with autism, due to individual and deficit differences which range broadly in ways that are not yet understood.

Another very important challenge is to build inherently safe robots that are easy to operate and affordable to a large segment of the population, as well as endorsed by education, health care, and elder care experts.

In summary, there is no shortage of scientific questions and challenges for this young and promising field.

B. Grand Challenges for Socially Assistive Robotics

Competitive challenges often have a stimulating effect on research, especially integrative experimental research that involves system integration and efforts of large numbers of people in collaborative teams. In robotics, competitions have a long history, ranging from robots running mazes (MicroMouse Competition), to playing soccer (RoboCup: Robot Soccer World Cup), to, most recently, autonomous off-road driving across a 142-mile desert route (DARPA Grand Challenge).

It is interesting and perhaps productive to consider what might constitute a grand challenge in socially assistive robotics. Naturally, the ultimate goal of the endeavor is the creation of systems capable of measurably helping people recover, train, and learn. The following is a possible series of realistic steps and milestones for a grand challenge:

- 1 year from today: Given a previously known condition (e.g., post-stroke, Alzheimer's, obesity) and a previously known controlled setting (e.g., a specific occupational therapy center, a specific elder care facility), create a physically embodied socially assistive system that helps the user in the given setting, is reported to be pleasant to interact with, and is sought out by the user for voluntary extended interactions over a period of several days.
  Consider the following example of post-stroke rehabilitation therapy: the socially assistive robot monitors the patient's movements and verbally interacts with him/her. When the patient stops performing the regular exercises, the robot encourages him/her verbally as a function of his/her personality type. The following is a possible script for an extroverted user: "Why did you stop? You have done only x exercises! The goal for today is y exercises! You can do more that that! I know it! Please continue!".
- 3 years from today: Given a previously known condition (e.g., post-stroke, Alzheimer's, obesity) and a previously known controlled setting (e.g., a specific occupational therapy center, a specific elder care facility, a specific well-mapped area of a private home), create a physically embodied socially assistive system that helps the user in the given setting, is reported to be pleasant to interact with, is sought out by the user for voluntary extended interactions over a period of a month, and demonstrates measurable adherence to the proscribed therapy/exercise/rehabilitation/learning regimen.
  Consider the following example of post-stroke rehabilitation therapy: the socially assistive robot monitors the patient's movements and verbally interacts with him/her as above. Moreover, the robot adapts its behavior on-line as a function of the patient's personality, mood, profile, preferences, and disability type and level. The robot adapts to the user over time, modifying its behavior naturally as a function of selected parameters, such as proxemics, activity, tone of voice, and vocal content. Therapy style can vary from nurturing ("You are doing great, please keep up the good work.") to challenging ("Come on, you can do better than that."), and extroverted (higher-pitched tone and louder volume) to introverted (lower-pitched tone and lower volume), in accordance with established personality theories. Through its behavior the robot attempts to encourage the patient and thereby improve patient task performance.
- 5 years from today: Given a previously known condition (e.g., post-stroke, Alzheimer's, obesity) and a general description of the setting (e.g., an occupational therapy center, an elder care facility, a private home), create a physically embodied socially assistive system that helps the user in the given setting, is reported to be pleasant to interact with, is sought out by the user for voluntary extended interactions over a period of several months, and demonstrates marked improvement in learning/training/recovery of the user in the given context.
  Consider the following example of post-stroke rehabilitation therapy: the socially assistive robot monitors the patient's movements, verbally interacts with him/her, and adapts its behavior on-line in accordance with the milestones referred to earlier. Additionally, the robot is endowed with articulated movement, allows for demonstrations of rehabilitation exercises and imitations of the user's performance to demonstrate errors and directions for improvement. The robot maintains a time-extended and incremental model of the user through life-long learning, allowing it to constantly adapt to remain effective as well as engaging.

The above grand challenge milestones are presented with the intention of stimulating discussion and long-range planning in the field of socially assistive robotics, as well as a potential inspiration for funding support toward relevant competitions that would serve to advance the field. They are merely examples from a vast range of possible grand challenge problems and demonstrations, any of which would have important impact on moving the field forward.

V. CONCLUSIONS

Early results already demonstrate the promises of socially assistive robotics, a new interdisciplinary research area with large horizons of fascinating and much needed research. Even as socially assistive robotic technology is still in its early stages of development, the next decade promises systems that will be used in hospitals, schools, and homes in therapeutic programs that monitor, encourage, and assist their users. This is an important time in the development of the field, when the board technical community and the beneficiary populations must work together to shape the field toward its intended impact on improved human quality of life.

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REFERENCES

[1] D. Feil-Seifer and M. J. Matarić, "Defining socially assistive robotics," in *Proc. IEEE International Conference on Rehabilitation Robotics (ICORR'05)*, Chicago, Il, USA, June 2005, pp. 465–468.

[2] J. Wada, T. Shibata, T. Saito, and K. Tanie, "Analysis of factors that bring mental effects to elderly people in robot assisted activity," in *Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS'02)*, Lausanne, Switzerland, Sept. 2000, pp. 1152–1157.

[3] A. Beck and A. Katcher, *Between Pets and People*. West Lafayette, IN: Purdue University Press, 1996.

[4] A. Katcher and G. Wilkins, "Dialogue with animals: Its nature and culture," in *The Biophilia Hypothesis*, S. R. Kellert and E. O. Wilson, Eds., Washington, DC, USA, 1993, pp. 173–197.

[5] C. G. Burgar, P. S. Lum, P. C. Shor, and M. V. Loos, "Development of robots for rehabilitation therapy: the palo alto va/stanford experience," *journal of Rehabilitation research and Development*, vol. 37, no. 6, pp. 639–652, 2000.

[6] J. Eriksson, M. J. Matarić, and C. Winstein, "Hands-off assistive robotics for post-stroke arm rehabilitation," in *Proc. IEEE International Conference on Rehabilitation Robotics (ICORR'05)*, Chicago, Il, USA, June 2005, pp. 21–24.

[7] R. Gockley and M. J. Matarić, "Encouraging physical therapy compliance with a hands-off mobile robot," in *Proc. of the First International Conference on Human-Robot Interaction (HRI'06)*, Salt Lake City, USA, Mar. 2006, pp. 150–155.

[8] A. Tapus and M. J. Matarić, "User personality matching with hands-off robot for post-stroke rehabilitation therapy," in *Proc. International Symposium on Experimental Robotics(ISER'06)*, Rio de Janeiro, Brazil, July 2006.

[9] K. I. Kang and M. J. Matarić, "A hands-off physical therapy assistance robot for cardiac patients," in *Proc. IEEE International Conference on Rehabilitation Robotics (ICORR'05)*, Chicago, Il, USA, June 2005, pp. 337–340.

[10] I. P. Werry and K. Dautenhahn, "Applying mobile robot technology to the rehabilitation of autistic children," in *Proc. of the 7th International Symposium on Intelligent Robotics Systems (SIRS'99)*, Coimbra, Portugal, July 1999.

[11] F. Michaud and A. Clavet, "Robotoy contest - designing mobile robotic toys for autistic children," in *Proc. of the American Society for Engineering Education (ASEE'01)*, Alberqueque, NM, USA, 2001.

[12] B. Scassellatti, "How social robots will help us to diagnose, treat and understand autism," in *Proc. of the 12th International Symposium of Robotics Research (ISSR'05)*, San Francisco, CA, USA, Oct. 2005.

[13] E. Mullen, *Mullen Scales of Early Learning: AGS Edition*. Circle Pines, MN: American Guidance Service, 1995.

[14] F. R. Volkmar, K. Charska, and A. Klin, "Autism in infancy and early childhood," *Annual Review of Psychology*, vol. 56, pp. 315–36, 2005.

[15] M. M. Ponty, *Phenomenology of Perception*. London: Routledge, 1962.

[16] B. Reeves and C. Nass, *The Media Equation: How People Treat Computers, Television, and New Media Like Real People and Places*. New York: Cambridge University Press, 1998.

[17] C. Breazeal, *Designing Sociable Robots*. Boston: MIT Press, 2002.

[18] J. Goetz and S. Kiesler, "Cooperation with a robotic assistant," in *Proc. International Conference on Computer-Human Interaction (CHI'02)*, Minneapolis, Minnesota, USA, Apr. 2002, pp. 578–579.

[19] H. Christensen and E. Pacchierotti, "Embodied social interaction for robots," in *Artificial Intelligence and Simulation of Behavior Convention (AISB'05)*, K. Dautenhahn, Ed., Hertsfordshire, UK, 2005, pp. 40–45.

[20] H. Nakajima, S. B. C. Nass, R. Yamada, Y. Morishima, and S. Kawaji, "The functionality of human-machine collaboration systems mind model and social behavior," in *Proc. of the IEEE Conference on Systems, Man, and Cybernetics*, Washington, USA, Oct. 2003, pp. 2381–2387.

[21] C. R. Rogers, "Empathy: An unappreciated way of being," *Counseling Psychologist*, vol. 5, pp. 2–10, 1975.

[22] C. L. Sidner and M. Dzikovska, "A first experiment in engagement for human-robot interaction in hosting activities," in *Advances in Natural Multimodal Dialogue Systems*, N. Bernsen, L. Dybkjaer, and J. van Kuppevelt, Eds., Dec. 2005.

[23] M. P. Michalowski, S. Sabanovic, and R. Simmons, "A spatial model of engagement for a social robot," in *Proc. of the International Workshop on Advanced Motion Control*, Istanbul, Turkey, Mar. 2006.

[24] A. Steinfeld, T. Fong, D. Kaber, M. Lewis, J. Scholtz, A. Schultz, and M. Goodrich, "Common metrics for human-robot interaction," in *Proc. of the First International Conference on Human-Robot Interaction (HRI'06)*, Salt Lake City, USA, Mar. 2006.

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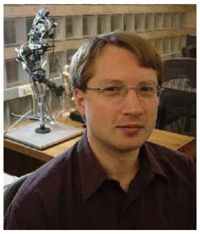

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