Human-Robot Interaction

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Glossary and Acronyms

Anthropomorphic: Resembling, or having the attributes of human form.
AR: Assistive Robotics
Autonomy: The ability to exert independent control, to self-direct.
Benchmarks: A standard used to measure performance.
Embodied: Having a physical form. Form exists in real-world.
GSR: Galvanic Skin Response
HCI: Human-Computer Interaction
HRI: Human-Robot Interaction
SAR: Socially Assistive Robotics
SIR: Socially Interactive Robotics
Robot: A mechanical system that takes inputs from sensors, processes them, and acts on its environment to perform tasks.
Tele-Operation: The act of controlling a device (such as a robot) remotely.

1 Definition of the Subject and Initial Use

Human-robot interaction (HRI) is the interdisciplinary study of interaction dynamics between humans and robots. Researchers and practitioners specializing in HRI come from a variety of fields, including engineering (electrical, mechanical, industrial, and design), computer science (human-computer interaction, artificial intelligence, robotics, natural language understanding, and computer vision), social sciences (psychology, cognitive science, communications, anthropology, and human factors), and humanities (ethics and philosophy).

2 Introduction

Robots are poised to fill a growing number of roles in today's society, from factory automation to service applications to medical care and entertainment. While robots were initially used in repetitive tasks where all human direction is given a priori, they are becoming involved in increasingly more complex and less structured tasks and activities, including interaction with people required to complete those tasks. This complexity has prompted the entirely new endeavor of Human-Robot Interaction (HRI), the study of how humans interact with robots, and how best to design and implement robot systems capable of accomplishing interactive tasks in human environments. The fundamental goal of HRI is to develop the principles and algorithms for robot systems that make them capable of direct, safe and effective interaction with humans. Many facets of HRI research relate to and draw from insights and principles from psychology, communication, anthropology, philosophy, and ethics, making HRI an inherently interdisciplinary endeavor.

3 Major HRI Influences in Popular Culture

Robots got their name in $\hat{C}$apek's play R.U.R. (Rossum's Universal Robots, 1921) [18]. In R.U.R., robots were man-made beings created to work for people and, as in many fictional stories thereafter, they went on to rebel and destroy the human race. In the 1950s, Isaac Asimov coined the term "robotics" and first examined the fundamental concepts of HRI, most prominently in his book *I, Robot* [3].

HRI has continued to be a topic of academic and popular culture interest. In fact, real-world robots have come into existence long after plays, novels, and movies developed them as notions and began to ask questions regarding how humans and robots would interact, and what their respective roles in society could be. While not every one of those popular culture works has affected the field of robotics research, there have been instances where ideas in the research world had their genesis in popular culture. In this section, significant popular culture products relating to HRI are overviewed, and their impact discussed.

The original benchmarks for HRI were proposed by Isaac Asimov in his now famous three laws of robotics:

1. *A robot may not injure a human being or, through inaction, allow a human being to come to harm.*
2. *A robot must obey orders given it by human beings except where such orders would conflict with the First Law.*
3. *A robot must protect its own existence as long as such protection does not conflict with the First or Second Law.*

In *I, Robot* [3], the three laws were examined relative to commands that humans give robots, methods for humans to diagnose malfunctions, and ways in which robots can participate in society. The theoretical implications of how the three laws are designed to work has impacted the way that robot and agent systems operate today [138], even though the type of autonomous reasoning needed for implementing a system that obeys the three laws does not exist yet.

Philip K. Dick's novel *Do Androids Dream of Electric Sheep* [23] (1968) is set in a future world (originally in the late '90s) where robots (called replicants) mingle with humans. The replicants are humanoid robots that look and act like humans, and special tests are devised to determine if an individual is a human or a replicant. The test is related to the Turing Test [130], in that both involve asking probing questions that require human experiences and capacities in order to answer correctly. As is typical, the story also featured a battle between humans and replicants.

George Lucas' *Star Wars* movies (starting in 1977) feature two robot characters (C3P0 and R2D2) as key characters, which are active, intuitive, even heroic. One of the most interesting features from a robot design point of view is that, while one of the robots is humanoid in form (C3PO) and the other (R2D2) is not, both interact effectively with humans through social, assistive, and service interactions. C3P0 speaks, gestures, and acts as a less-than-courageous human. R2D2, on the other hand, interacts socially only through beeps and movement, but is understood and often preferred by the audience for its decisiveness and courage.

In the television show *Star Trek: The Next Generation* (1987-1994), an android named Data is a key team member with super-human intelligence but no emotions. Data's main dream was to become more human, finally mastering

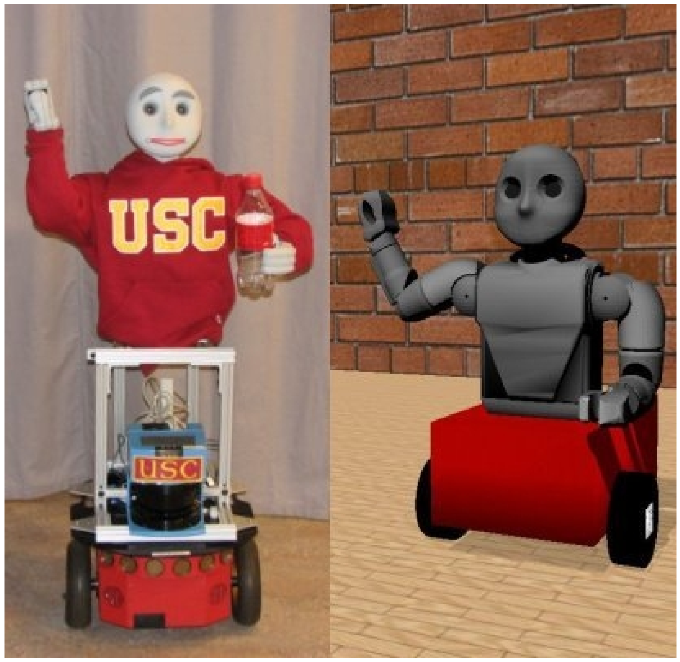

Figure 1: An example of an HRI testbed: a humanoid torso on a mobile platform, and a simulation of the same system.

emotion. Data progressed to becoming an actor, a poet, a friend, and often a hero, presenting robots in a number of potentially positive roles.

The short story and movie *The Bicentennial Man* [4], features a robot who exhibits human-like creativity, carving sculptures from wood. Eventually, he strikes out on his own, on a quest to find like-minded robots. His quest turns to a desire to be recognized as a human. Through cooperation with a scientist, he develops artificial organs in order for him to bridge the divide between himself and other humans, benefiting both himself and humanity. Eventually, he is recognized as a human when he creates his own mortality.

These examples, among many others, serve to frame to scope of HRI research and exploration. They also provide some of the critical questions regarding robots and society that have become benchmarks for real-world robot systems.

4 Prominent Research Challenges

The study of HRI contains a wide variety of challenges, some of them of basic research nature, exploring concepts general to HRI, and others of domain-specific nature, dealing with direct uses of robot systems that interact with humans in particular contexts. In this paper, we overview the following major research challenges within HRI: multi-modal sensing and perception; design and human factors; developmental and epigenetic robotics; social, service and assistive robotics; and robotics for education. Each is discussed in turn.

4.1 Multi-Modal Perception

Real-time perception and dealing with uncertainty in sensing are some of the most enduring challenges of robotics. For HRI, the perceptual challenges are particularly complex, because of the need to perceive, understand, and react to human activity in real-time.

The range of sensor inputs for human interaction is far larger than for most other robotic domains in use today. HRI inputs include vision and speech, both major open challenges for real-time data processing. Computer vision methods that can process human-oriented data such as facial expression [10] and gestures [25] must be capable of handling a vast range of possible inputs and situations. Similarly, language understanding and dialog systems between human users and robots remain an open research challenge [47, 139]. Tougher still is to obtain understanding of the connection between visual and linguistic data [104] and combining them toward improved sensing [110] and expression [14].

Even in the cases where the range of input for HRI-specific sensors is tractable, there is the added challenge of developing systems that can accomplish the sensory processing needed in a low-latency timeframe that is suitable for human interaction. For example, Kismet [13], an animated robotic head designed for infant-like interactions with a human, using object tracking for active vision, speech and prosody detection and imitation, and an actuated face for facial expressions, required several computers running in tandem to produce engaging if non-sensical facial and speech behavior. The humanoid ASIMO has been adapted to use a combination visual-auditory system for operation in indoor environments [107]. ASIMO's subsystems were used for perception, planning, and action with the goal of enabling human-robot interaction. Adding meaning to the facial and physical expressions and speech, and combining all of those capabilities in real time on a mobile, self-contained robot platform, is still an open research problem in HRI.

Even though most implemented HRI systems are necessarily domains-specific, as all physical systems, they still require the additional step of generalization to make them work beyond the research lab context. Computer vision solutions often depend on specific lighting conditions [49], ambient colors [114], and objects in the scene [15]. Beyond the lab, either the environment must be constrained to match the acceptable conditions for system operation [128], or the system capabilities must be extended in order to meet the range of conditions in the specific destination environment [81].

In addition to robot sensors that mimic the functionality of human perception (speech recognition, computer vision, etc.), sensors are being developed that cater to the unique perceptual capabilities of robots. These sensors enable a machine to observe people and the environment in ways that may be beyond human access. Physiological signals, such as heart rate, blood pressure, galvanic skin response (GSR, the measure of skin conductance using a galvanometer), provide information about the user's emotional state [60, 84, 112] that may not otherwise be observable. Work by Mower et al. [88] used GSR as part of an HRI system to model and predict when a user is about to quit a rehabilitation-type task.

Body pose and movement are important sources of information for social interaction [104]. For example, social and expressive gestures are crucial components of human-human and human-robot interaction [119]. Computer vision can provide such information in limited contexts. In others, wearable sensors may be an effective means of obtaining human activity data in real time with high accuracy [83]. Such wearable systems have been used in HRI tasks applied to physical rehabilitation post-stroke [32], and for social interaction [122].

In addition to developing new and improving existing sensors toward particular needs of HRI, researchers are also developing algorithms for integrating multi-sensor multi-modal data inherent to HRI domains [29, 42, 89, 91, 107]. For example, Kapoor and Picard [55] implemented an affect recognition system that applies Gaussian models to fuse multiple sensors. Multi-modal sensing has also been used for a robot to detect the attention of human users in order to determine if a user is addressing the robot [69], integrating person tracking, face recognition [12], sound source localization [133], and leg detection [82].

4.2 Design and Human Factors

The design of the robot, particularly the human factor concerns, are a key aspect of HRI. Research in these areas draws from similar research in human-computer interaction (HCI) but features a number of significant differences related to the robot's physical real-world embodiment. The robot's physical embodiment, form and level of anthropomorphism, and simplicity or complexity of design, are some of the key research areas being explored.

Embodiment The most obvious and unique attribute of a robot is its physical embodiment. By studying the impact of physical embodiment on social interaction, HRI researchers hope to find measurable distinctions and trade-offs between robots and non-embodied systems (e.g., virtual companion agents, personal digital assistants, intelligent environments, etc.).

Little empirical work to date has compared robots to other social agents. Work by Bartneck et al. [9] claimed that robotic embodiment has no more effect on people's emotions than a virtual agent. Compelling recent work [58] used three characters, a human, a robot, and an animated character, to verbally instruct participants in a block stacking exercise. The study reported differences between the embodied and non-embodied agents: the robot was more engaging to the user than a simulated agent. Woods et al. [144] studied perception differences between live and video recorded robot performances. They proposed using video recordings during system development as a complementary research tool for HRI.

Recent findings [136, 137] suggest that there are several key differences between a robot and virtual agent in the context of human-machine interaction. The three conditions explored in that work (a physical robot body, a physical robot located elsewhere through a video link, and a simulation of a robot) were an attempt to control variables in order to isolate the effects of embodiment from realism. The researchers surveyed the participants regarding various properties related to the interaction. The results showed that the embodied robot was viewed by participants as more watchful, helpful, and appealing than either the realistic or non-realistic simulation.

Much work remains to be done in order to address the complex issues of physical embodiment in human-machine interaction. One confounding factor of this study involves the robot's form, discussed next.

Anthropomorphism The availability and sophistication of humanoid robots has recently soared. The humanoid form allows for exploring the use of robots for a vast variety of general tasks in human environments. This propels forward the various questions involved in studying the role of anthropomorphism in HRI. Evidence from communications research shows that people anthropomorphize computers and other objects, and that that anthropomorphism affects the nature of participant behavior during experiments [102].

HRI studies have verified that there are differences in interaction between anthropomorphic and non-anthropomorphic robots. For example, children with autism are known to respond to simple mobile car-like robots as well as to humanoid machines. However, pilot experiments have suggested that humanoid robots may be overwhelming and intimidating, while others have shown therapeutic benefit [105, 108]. Biomimetic, and more specifically, anthropomorphic form allows human-like gestures and direct imitation movements, while non-biomimetic form preserves the appeal of computers and mechanical objects.

Several examinations have been performed of the effects of anthropomorphic form on HRI [28]. These include studies of how people perceive humanoid robots compared to people and non-humanoid robots [97], possible benchmarks for evaluating the role of humanoid robots and their performance [52], and how the design of humanoid robots can be altered to affect user interacts with robots [24].

Simplicity/Complexity of Robot Design The simplicity/complexity of the robot's expressive behavior is related to the biomimetic/anthropomorphic property. Researchers are working to identify the effect that simple v. complex robot behavior has on people interacting with robots. For example, Parise et al. [98] examined the effects of life-like agents on task-oriented behavior. Powers and Kiesler [101] examined how two forms of agent embodiment and realism affect HRI for answering medical questions. Wainer et al. [136, 137] used a similar experimental design to explore the effects of realism on task performance. In those studies, the more realistic or complex a robot was, the more watchful it seemed. However, it was also found that participants were less likely to share personal information with a realistic or complex robot.

Other Attributes In Reeves and Nass [102], several human factors concepts are explored in relation to human-computer interaction (HCI). As researchers work to better understand human-robot interaction, human factors insights from HCI can be valuable, but may not always be relevant. Lee and Nass [73] examined the relationship between a a virtual agent's voice and its personality. The authors found that users experienced a stronger sense of social presence from the agent when the voice type and personality matched, than when they did not. In an HRI study, Tapus and Matarić [124] showed that when a robot's expressive personality matched the user's personality, task performance was better than when the personalities were mismatched. Robles et al. [106] used agents that gave feedback for a speed-dating application to examine users' feelings regarding monitoring (public and private), conformity, and self-consciousness. This study correlated users' actions with surveyed perceptions regarding feedback to determine how feedback can be most effectively given, and how it can be given in as effective a context as possible. Kidd and Breazeal [58] used a similar design to evaluate how a robot (compared to an agent or to a human) can give feedback for making decisions.

Ongoing research is also exploring how cultural norms and customs can affect the use of computer agent and robot systems. For example, Takeuchi et al. [123] designed an experiment to test the differences in behavior reciprocity between users of a virtual agent in the U.S. and users in Japan. They discovered that users from both countries expressed attitudes consistent with behavior reciprocity, but only U.S. users exhibited reciprocal behavior. However, they discovered that when recognizable brands from popular culture were used, then reciprocal behavior was exhibited in Japanese users as well.

4.3 Developmental/Epigenetic Robotics

Developmental robotics, sometimes referred to as epigenetic robotics, studies robot cognitive development. Developmental roboticists are focused on creating intelligent machines by endowing them with the ability to autonomously acquire skills and information [140]. Research into developmental/epigenetic robotics spans a broad range of approaches. One effort has studied teaching task behavior using shaping and joint attention [15], a primary means used by children in observing the behavior of others in learning tasks [90, 92]. Developmental work includes the design of primitives for humanoid movements [26], gestures [67], and dialog [113].

Figure 2: Examples of SAR research. Left: post-cardiac surgery convalescence. Middle: post-stroke rehabilitation. Right: cognitive and physical exercises.

While developmental/epigenetic robotics is not a direct subset of HRI research, there is significant overlap in the goals of the two areas. Developmental techniques for information acquisition share much in common with multi-modal perception. Epigenetic research into pronoun learning has overlap with social robotics [39]. Finally, techniques for automated teaching and learning of skills has direct applications for algorithm development for education robotics [64, 93]. This work involves estimating behavior from human actions [65]. In the broader field of robot learning, a variety of methods are being developed for robot instruction from human demonstration [42, 66, 94, 100], from reinforcement learning [132], and from genetic programming [95], among others.

4.4 Social, Service, and Assistive Robotics

Service and assistive robotics [31] include a very broad spectrum of application domains, such as office assistants [5, 41], autonomous rehabilitation aids [79], and educational robots [126]. This broad area integrates basic HRI research with real-world domains that required some service or assistive function. The study of social robots (or socially interactive robots) focuses on social interaction [33], and so is a proper subset of problems studied under HRI.

Assistive robotics itself has not been formally defined or surveyed. An assistive robot is broadly defined as one that gives aid or support to a human user. Research into assistive robotics includes rehabilitation robots [16, 27, 45, 51, 76], wheelchair robots and other mobility aides [2, 38, 116, 145], companion robots [8, 99, 134], manipulator arms for the physically disabled [37, 40, 57], and educational robots [53]. These robots are intended for use in a range of environments including schools, hospitals, and homes. In the past, assistive robotics (AR) has largely referred to robots developed to assist people through physical interaction. This definition has been significantly broadened in the last several years, in response to the growing field of AR in which assistive robots provide help through non-contact, social interaction, defining the new field of socially assistive robotics (SAR).

Socially assistive robotics (SAR) is a growing area of research with potential benefits for elder care, education, people with social and cognitive disorders, and rehabilitation, among others. SAR is the intersection of assistive robotics, which focuses on robots whose primary goal is assistance, and socially interactive robotics [33], which addresses robots whose primary feature is social interaction. SAR arose out of the large and growing body of problem domains suitable for robot assistance that involves social rather than physical interaction [75, 127, 142].

In rehabilitation robotics, an area that has typically developed physically-assistive robots, non-contact assistive robots are now being developed and evaluated. These robots fulfill a combined role of coach, nurse, and companion in order to motivate and monitor the user during the process of rehabilitation therapy. Observing the user's progress, the robots provide personalized encouragement and guidance. Applications for post-operative cardiac surgery recovery [54] and post-stroke rehabilitation [79] have been studied. Other rehabilitation projects have explored using a robot as a means of motivating rehabilitation through mutual storytelling [70, 99]. In these experiments, a robot and a user constructs a story, which, when acted out, require the user to perform physical therapy exercises.

A variety of assistive robotics systems have been studied for use by the elderly. Such robots are meant to be used in the home, in assisted living facilities, and in hospital settings. They work to automate some physical tasks that an elderly person may not be able to do, including feeding [57], brushing teeth [129], getting in and out of bed, getting into and out of a wheelchair, and adjusting a bed for maximum comfort [50]. In some cases, the robots are envisioned as part of a ubiquitous computing system [50], which combines cameras and other sensors in the environment and computer controlled appliances (such as light switches, doors, and televisions) [8]. In others, the robots serve SAR roles such as promoting physical and cognitive exercise [125].

HRI systems have been used as companion robots in the public areas of nursing homes, aimed at increasing resident socialization. These robots are designed not to provide a specific therapeutic function, but to be a focus of resident attention. One such example is the huggable, a robot outfitted with several sensors to detect different types of touch [121]. Another such example is NurseBot, a robot used to guide users around a nursing home [85]. Paro [134, 135], an actuated stuffed seal, behaves in response to touch and sound. Its goal is to provide the benefits of pet-assisted therapy, which can affect resident quality of life [30], in nursing homes that cannot support pets. Initial studies have shown lowered stress levels in residents interacting with this robot, as well as an overall increase in the amount of socialization among residents in the common areas of the same facility.

Finally, HRI is being studied as a tool for diagnosis [108, 109] and socialization [22, 68, 81, 141] of children with autism spectrum disorders (ASD). When used for diagnosis, robots can observe children in ways that humans cannot. In particular, eye-tracking studies have shown remarkable promise when evaluating children for the purposes of diagnosing ASD. In terms of socialization, robots are a more comfortable social partner for children with ASD than people. These robots encourage social behavior, such as dancing, singing, and playing, with the robot and with other children or parents in the hope of making such behavior more natural.

4.5 Educational Robotics

Robotics has been shown to be a powerful tool for learning, not only as a topic of study, but also for other more general aspects of science, technology, engineering, and math (STEM) education. A central aspect of STEM education is problem-solving, and robots serve as excellent means for teaching problem-solving skills in group settings. Based on the mounting success of robotics courses world-wide, there is now is an active movement to develop robot hardware and software in service of education, starting from the youngest elementary school ages and up [48, 77, 78]. Robotics is becoming an important tool for teaching computer science and introductory college engineering [78].

Robot competition leagues such as Botball [120], RoboCup [118] and FIRST [96] have become vastly popular. The endeavors encourage focused hands-on problem solving, team work, and innovation, and range from middle- and high-school-age children up to university teams. Educators are also using robots as tools for service learning, where projects are designed for assistive domains. Innovative teaching methods include competitions to develop robot toys for children with ASD [80] and other assistive environments [46].

In some specific domains, robots have been shown to be better for instruction than people [71]. While some automated systems are used for regular academic instruction [43], others are used for social skill instruction. In particular, robots can be used to teach social skills such as imitation [105], self-initiation of behavior [63], and are being explored as potentially powerful tools for special education [56].

5 Benchmarks and Ethical Issues for HRI

As HRI systems are being developed, their impact on users and society at large are increasingly being considered. Currently, it is difficult to compare robotic systems designed for different problem domains, yet it is important to do so in order to establish benchmarks for effective and ethical HRI design. Kahn et al. [52] argued for comparative methods and proposed benchmarks for HRI, with a particular focus on gaining a better understanding humanoid robots designed for HRI.

One of the most challenging aspects of establishing such benchmarks is that many aspects of HRI are difficult to measure. Establishing whether or not a robot can make eye contact with a person is comparatively simple (if not always easy to implement), but evaluating how the person reacts to and is affected by the robot's gaze and behavior is much more difficult. Does the user get bored or frustrated? Does the user consider the robot helpful and effective? Is the robot perceived as competent? Is it trusted to perform its intended tasks?

These and related questions lead to ethical considerations and legal guidelines that need to be addressed when developing HRI systems. Not only do roboticists need to act ethically, the robots themselves must do so as well. Challenges to be considered include unintended uses of the robot, allowable tasks, and unintended situations that might be encountered. For example, if the user needs emergency attention, what is the robot's responsibility? Furthermore, the issue of control has important implications. While it is assumed the user is in control, in a variety of situations (dispensing medicine, dealing with cognitively incapacitated users) the control responsibility must rest with the machine. The issue of control and authority thus extends to all involved with the machine, including caretakers, and even designers and programmers. Well-studied ethical challenges are gradually making their way into HRI as the systems are growing in complexity and usefulness, and as their likelihood of entering human daily life increases.

5.1 General Benchmarks and Ethical Theory

While no specific ethical guidelines have yet been established, active discussions and task forces have taken up this challenging problem. Turkle [131] addressed the attachment that occurs between humans and robots when residents of a nursing home are asked to "care for" a baby-like robot. The users in the experiment ascribed human-like qualities to the robot, resulting in side-effects with ethical ramifications. What happens when the robot breaks down? What if the robot is taken away? Some benchmarks address the disparity between machines that exist only to serve a human "master" and those that exist in cooperation with their users and act with autonomy [52]. Is it acceptable for people to treat a social being like a slave?

The nature of morality for androids and other artificially intelligent entities has also been explored [138] and the difference between top-down and bottom-up morality defined. A top-down approach to morality is any approach that takes an ethical theory and guides the design and implementation of algorithms and subsystems capable of implementing that ethical theory. A bottom-up approach involves treating values as implicit to the design of the robot. In that work, morality (either implied or explicitly programmed) helps guide the behavior of robots to effectively work with humans in social situations.

Yanco [145] described the evaluation of an assistive robot, stating that such evaluation can be done through user tests and comparison to a human in the same assistive role. Long-term studies were recommended in order to evaluate effectiveness in real-world settings. Others advocated a human-centered approach to design, suggesting ecological studies of the use of the robots in the intended environment rather than long-term user studies [35].

5.2 Robot Evaluation

Any robot is a physical and technological platform that must be properly evaluated. In this section, two evaluation benchmarks of particular concern to HRI, safety and scalability, are discussed.

Safety Safety is an important benchmark for HRI: *How safe is the robot itself, and how safe can the robot make life for its user?*

A robot's safety in its given domain is the primary concern when evaluating an HRI system. If a robot is not designed with safety in mind, it could harm the very users it is designed to interact with. A key advantage of HRI over physically assistive robots is the minimization of the inherent safety risk associated with physical contact. When discussing safety pertaining to a mobile platform, we refer to the ability to maneuver about a scene without unwanted contact or collisions. Safety also refers to protection (as much as it is possible) of a robot's user and of the robot itself. This concept, as a benchmark, refers to safety in a bottom-up fashion, rather than Asimov's laws which refer to the concept in a top-down fashion [138].

Safety for assistive robots has been studied in depth in the contexts of obstacle avoidance for guide-canes and wheelchairs [7, 103, 145]. Robots have also been designed to help users navigate through a nursing home [38, 87]. The need for safety assessment for HRI systems designed for vulnerable user populations is a topic of growing importance as HRI systems are increasingly being developed toward users from such populations.

Scalability The majority of current HRI work occurs in research laboratories, where systems are engineered for one environment and a pre-determined prototype user population. As HRI becomes more widespread in homes, schools, hospitals, and other daily environments, the question of scalability and adaptability arises: *How well will such HRI systems perform outside of the lab?* and: *How well does a robot perform with users from the general population?*

The scalability benchmark does not imply that roboticists should design each robot for a large a variety of situations where assistance is required. Rather, it is important to stress that, even within a group that needs assistance, there is a great difference between a "prototypical" user or environment and the range of real-world users and environments.

Another key question to address is: *How many people can be helped by such a robot?*. Consider, for example, a robot that uses speech recognition for understanding a user's intentions. How does speech recognition perform when the speaker has recently suffered a stroke? Can the robot interact with someone who cannot speak? If the robot is meant to be a companion for a user, can the robot adapt its behavior to different users? How difficult is it for the robot to be modified for different needs?

In addition to user population scalability, the range of usable environments is an important benchmark. Most systems to date have been tested in research labs or controlled hospital and managed care settings. In the future, however, HRI systems will be used in homes and other more unpredictable environments. In such domains, the following benchmark becomes relevant: *Can the robot operate in the most relevant environments for the user?*

5.3 Social Interaction Evaluation

A critical benchmark of HRI is the evaluation of the robot as a social platform. Social interaction and engagement are both the primary means of interaction and the driving force behind the design. When assessing a robot in terms of social performance, we must also consider the larger goal of the robot in its application context.

Previously proposed benchmarks for humanoid robots [52] are directly relevant to HRI as well. In many respects, the same comparisons and evaluations that hold for humanoid robotics also hold for HRI. However, the goal of HRI is not to make as interesting or realistic a robot as possible, but to make a robot that can best carry out its task. It is important, therefore, to evaluate HRI not only from a perspective of modeling human characteristics, but also from a user-oriented perspective. The following sections describe how some of the previously identified humanoid benchmarks that relate to HRI.

Autonomy Autonomy is a complex property in the HRI context. It is favorable, when constructing a system that is designed to stand in for a human in a given situation, to have a degree of autonomy which allows it to perform well in its desired tasks. Autonomy can speed up applications for HRI by not requiring human input, and by providing rich and stimulating interactions. For example, HRI systems for proactive social interaction with children with ASD [22] and motivational robot tools [79, 124, 136] require such autonomy. However, autonomy can also lead to undesirable behavior. In situations such as medication dispension and therapy monitoring [36], for example, autonomy is not desirable.

In general, HRI contexts require engaging and believable social interaction, but the user must clearly retain authority. For example, rehabilitation should terminate if the user is in pain. Social interaction should only occur when it is tolerable for the user. Partial or adjustable autonomy on the part of the HRI system allows for an appropriate adjustment of both authority and autonomy.

Imitation Alan Turing proposed a test of artificial intelligence (AI), whereby a system is evaluated by whether it could fool a human user communicating with it through teletype [130]. This test was later elaborated to the Total Turing Test [44], where a system communicating in human-like ways (text, speech, facial expressions) tries to fool a human user into believing it is human. Since that time, one of the benchmarks for success in AI and HRI has been how well the system can imitate human behavior. However, when dealing with goal-oriented systems not primarily relating to human behavior but rather to assistance and treatment, imitating human behavior is necessarily desirable.

It has been shown that a robot's personality can effect a user's compliance with that robot [59]. When exhibiting a serious personality, the robot could provoke a greater degree of compliance than displaying a playful personality. It has also been shown that when the robot's extroversion/introversion personality traits matched the user's, task performance was improved [124]. Thus, the imitation benchmark proposed by Kahn could be revised for HRI: *How do imitation and reciprocity affect task performance?*

While no definitive evidence yet exists, there is a good deal of theory regarding a negative correlation between the robot's physical realism and its effectiveness in human-robot interaction. Realistic robotics introduces new complications to social robot design [28] and it has been implied that anthropomorphism has a negative influence on social interaction when the robot's behavior does not meet a user's expectations [115]. The Uncanny Valley theory suggests that as a robot becomes very similar in appearance to a human, that robot appears less, rather than more, familiar [86]. Physical similarity that attempts in imitation of human-like appearance and behavior could cause discord. This leads to two possible benchmark for imitation: *Does the interaction between the human and the robot reflect an accurate and effective impression of the robot's capabilities?* and *Does the interaction between the human and the robot allow for the expression of the human's capabilities?*

Privacy The presence of a robot inherently affects a user's sense of privacy [52]. In contrast to ubiquitous systems [11, 61, 74] where a user has no idea of when the system may be watching, robots are tangible and their perception limited and observable. A robot can be told to leave when privacy is desired, and the user can observe when privacy is achieved. Because of its synthetic nature, a robot is perceived as less of a privacy invasion than a person, especially in potentially embarrassing situations. Privacy is thus of particular concern for designers of assistive systems [6]. Therefore, a possible benchmark from an HRI perspective asks: *Does the user's perceived sense of privacy relate to better robot performance as an assistive presence?*.

5.4 Task-Oriented Benchmarks

The interactive, task-oriented nature of HRI suggests some additional benchmarks. Task performance is described as the ability of the robot to assist a user in a given task. The benchmarks then pertain to how the social aspects of the robot affect the overall task performance of the robot and its user. As with the other benchmarks, discussed above, these could apply to all social robots, but when put into an assistive context, the task-related effects highlight these features.

Social Success *Does the robot successfully achieve the desired social identity?* This is perhaps the most amorphous of benchmarks, but its evaluation is simple. When the robot is intended to be playful, do users find the robot playful? If the robot is supposed to be a social peer, do users act as if it were a social peer? How does the intended social identity compare to what occurs in practice? This benchmark is not meant to judge the ability of the robot system designer to generate a suitable robot personality. The social success of the robot is a fundamental component of HRI applications. As discussed above, the social identity of the robot (both the personality and the role of the robot) has an effect on the user's task performance.

Understanding of Domain Understanding of social dynamics is a critical component of HRI. Roboticists employ user and activity modeling as means of achieving such understanding. Efforts to understand a user of an HRI system include emotion recognition [19, 20], and integration of vocalizations, speech, language, motor acts, and gestures [17, 72] for effectively modeling user state.

Sensing social understanding and engagement can be be assessed through a variety of means. Earlier in this document we discussed the use of GSR to assess user state. Roboticists have also used radio frequency identification (RFID) tags and position tracking to observe children in school hallways to detect when users were in social range, and who they were interacting with over time [53], to help the robot determine appropriate social responses. Thus, social understanding in HRI can come from both human-oriented social perception (such as the interpretation of gestures, speech, and facial expressions), and from an evaluation of user physiologic state (such as GSR, heart rate, temperature, etc.). How such data are used leads to the following benchmark: *Does a robot's social understanding of human behavior help task performance?*

5.5 Assistive Evaluation

There are many ways to view an assistive tool. For the domains of HRI, impact on user's care, impact on caregivers, impact on the user's life, and the role of the robot are the key benchmarks for an assistive platform. An important way to view how an assistive robot performs when caring for people is by first observing how people care for other people in similar situations. The role of an assistive robot may be that of a stand-in for a human caregiver, a complement for a human caregiver, or an assistant to a human caregiver. Naturally, the benchmarks have different application in various scenarios. As with the other benchmarks, discussed above, this is not meant to be a comprehensive list, but a consideration of some of the most relevant benchmarks.

Success Relative to Human Caregiver A good place to start when evaluating the effect a robot has on a user's care is to compare the results of care with a robot caregiver to that of care with a human caregiver: *How does the robot perform relative to a human performing the same task?* When such evaluation is possible, existing metrics can be applied. For example, in rehabilitation tasks, functional improvement can be a metric [79]. For learning tasks, overall learning measures such as grades, tests, or evaluations can be used. In the spirometry task where a robot instructed a cardiac surgery patient to do breathing exercises [54], compliance with the robot compared to compliance with a human was a suitable metric. For companion robots, evaluating user satisfaction is most relevant.

A key role of assistive HRI is to provide care where human care is not available. In many cases, the type of interaction that is established in HRI is not directly comparable to human care, and in some instances, human care is not available for comparison. In all cases, the user satisfaction and motivation to engage in the relevant activities is a key metric of system effectiveness, on par with functional measures of task performance.

Cost/Benefit Analysis The robot can perform in several different capacities for any given task. For example, in a rehabilitation setting a robot could serve as therapist, giving advice on specific movements, a motivational coach, giving general encouragement and monitoring progress, a cognitive orthotic, reminding the users of important items, a companion, a learning aid, or as a demonstration, showing a user how to do specific exercises. The role of the robot for a given task can inform the complexity and sophistication of the robot and its social and assistive capacities.

An ethnographic study used readily-available low-cost robot vacuum cleaners to determine the role that the robots played in household [34]. The study used home tours and semi-structured interviews to create an ecological model of the home. The data provided insights into how a service robot might be treated, and how close the real users came to the design intention of the robot. Some treated the robot as if it were a member of the household, with status roughly between the vacuum cleaner and a pet. Others treated it strictly as a device with a purpose. An interesting observation is that men got more involved in cleaning tasks associated with the Roomba (pre-cleaning, activation, and emptying the unit when the task was completed).

HRI is intended as a tool for creating robotic systems capable of providing cost-effective solutions to a variety of applications. Cost/benefit analysis can thus a benchmark for success for such systems. In domains where no alternatives exist, and where HRI systems provide a novel and only solution, have the potential of creating major societal impact. Health care is one such domain. This suggests two benchmarks for HRI: *Does the use of the robot (a) change the cost/benefit ratio of providing such care or (b) make such care available where it was not previously possible?*

Impact on Caregivers In some cases, the goal of automation is not to increase the efficiency, productivity, or standard of care, but to make the user's or caregivers' job easier and more manageable. For example, the goal of the robot described above in Kang et al. [54] was to reduce the overall workload for cardiac nurses, given the overall nurse shortage in the US and world-wide. The robot visited cardiac patients post-surgery, approached each patient's bed, encouraged the patient to perform the breathing exercise, monitored the number and depth of the breaths taken, and collected performance data. By automating the prompting and monitoring of spirometry, which must be performed ten times per hour for the critical post-surgery period, the robot made it possible for caregivers to attend to other tasks and provide more individualized services. However, in this case, the robot did not provide any care not already provided by a human caregiver.

Caregiver impact is thus a useful benchmark: *Does the job condition of the caregiver improve as a result of the robot?* Additionally, it is important to observe cooperation: *How well does the caregiver work with the robot?* This arises out of a concern that trained and experienced caregivers are not used to working with robots, and may need to adjust their work habits [111].

Satisfaction With Care User satisfaction is an important aspect of assistive therapy success. Users' impression of a nurse robot's personality affects compliance with that robot, both positively and negatively [59]. Satisfaction, therefore can be a useful benchmark for success. Questionnaires are being explored [136, 137] to measure satisfaction, although little work to date has directly related satisfaction with a robot system to task performance or user compliance. An important question when designing an assistive system is raised: *Does user satisfaction with a system affect the assistive task performance and/or user compliance?*

Existing Quality of Life Measures Evaluating the effects of a particular therapy regimen must be done relative to the overall quality of life (QoL) of the user [143]. Some recommend using repeated measures with the same survey to capture changes over time. The SF-36 survey is designed for patient rating of health-related quality of life [1]. This survey assesses the comprehensive quality of life from the patient's point of view. The 15-D survey produces quality of life numbers along several dimensions [117]. In addition to such quantifiable measures, experiential measures, such as the Dementia Care Mapping (DSM), are also used broadly [62]. Such measures bring to the forefront the users of a particular type of service [146], as well as the notion that socially-sensitive care (involving eye-contact, favorable attention, etc.) is important to the overall outcome. This leads to a suitable HRI benchmark: *Does the robot result in a general increase in the quality of life as perceived by the user?*

Impact on the Role in Community/Society The introduction of automation and HRI-capable systems has an affect the user community. When fish tanks were introduced into a nursing home environment to test the effects on residents, observers found an overall increase in nutrition on the part of the participating residents [30]. A side-effect of the installation of the fish tanks was that residents gathered around those situated in common areas and engaged in more conversation than was previously observed. The introduction of new objects of social interest into an environment can thus change the dynamics of the community.

When roboticists introduced the robot seal Paro into the common areas of a nursing home [134, 135], they found a reduction of stress proteins in the urine of the participants. Another positive effect of the experiment was that residents were in the common areas longer and socialized more. The Robovie project was able to use a robot to stimulate social interaction among a group of elementary school students [53]. By telling "secrets" about itself, the robot was able to elevate a student's status in the group by giving him/her special information [21].

A potential critique of assistive robotics is that social robots capable of HRI could reduce the amount of human contact for their users. Thus, when assessing a particular robot-assisted therapy, it is important to note not only the immediate effects on a single user, but also the effects that the robot has on the community as a whole: *Does the robot increase or decrease the amount of socialization in its user community?* and: *Are changes in community due to a robot positive or negative?*

6 Notable Conferences

HRI is an active and growing area of research. Progress in the field is discussed and showcased at a number of conferences, symposia, and workshops. Research results are published both in new and growing HRI conferences and journals, and the more established venues of the parent fields of HRI, namely robotics and AI.

6.1 Human-Robot Interaction-Specific Conferences

- **Conference on Human Robot Interaction (HRI):** This conference, created in 2006, is focused specifically on HRI research. Attendees and submissions to this conference are mostly from engineering (electrical engineering and computer science) with contributions from allied fields, such as psychology, anthropology, and ethics.

- **International Workshop on Robot and Human Interactive Communication (RO-MAN):** RO-MAN provides a forum for an interdisciplinary exchange for researchers dedicated to advancing knowledge in the field of human-robot interaction and communication. Importantly, RO-MAN has traditionally adopted a broad perspective encompassing research issues of human-machine interaction and communication in networked media as well as virtual and augmented tele-presence environments. RO-MAN is somewhat longer-standing than HRI.

- **International Conference on Development and Learning (ICDL):** This conference brings together the research community at the convergence of artificial intelligence, developmental psychology, cognitive science, neuroscience, and robotics, aimed at identifying common computational principles of development and learning in artificial and natural systems. The goal of the conference is to present state-of-the-art research on autonomous development in humans, animals and robots, and to continue to identify new interdisciplinary research directions for the future of the field.

- **Computer/Human Interaction (CHI) Conference:** CHI is an established conference in Human-Computer Interaction (HCI). Every year, it is a venue for 2000 HCI professionals, academics, and students to discuss HCI issues and research and make lasting connections in the HCI community. HRI representation in this meeting is small, but the two fields (HRI and HCI) have much to learn and gain from each other.

6.2 General Robotics and AI Conferences

- **Association for the Advancement of Artificial Intelligence (AAAI):** AAAI's annual conference affords participants a setting where they can share ideas and learn from each other's artificial intelligence (AI) research. Topics for the symposia change each year, and the limited seating capacity and relaxed atmosphere allow for workshoplike interaction.

- **AAAI Spring and Fall Symposia:** These annual symposia cover a broad range of focused topics. With the rapid growth of HRI, the topic and related areas (e.g., service robotics, socially assistive robotics, etc.) symposia are held in each session.

- **Epigenetic Robotics (EpiRob):** The Epigenetic Robotics annual workshop has established itself as an opportunity for original research combining developmental sciences, neuroscience, biology, and cognitive robotics and artificial intelligence is being presented.

- **International Conference on Robotics and Automation (ICRA):** This is one of two most major robotics conferences, covering all areas of robotics and automation. In recent years, the themes of the conference have included many areas of HRI research, such as "Humanitarian Robotics," "Ubiquitous Robotics," and "Human-Centered Robotics", reflecting the rapid growth in the field.

- **International Conference on Intelligent Robots and Systems (IROS):** This is the other major international robotics conference, featuring a very large number of papers, with a growing representation of HRI. Tutorials and workshops, as well as organized/special sessions in HRI are featured regularly.

- **International Symposium on Experimental Robotics (ISER):** ISER is a single-track symposium featuring around 50 presentations on experimental research in robotics. The goal of these symposia is to provide a forum dedicated to experimental robotics research with principled foundations. HRI topics have become a regular part of this venue.

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