Teleoperation and Beyond for Assistive Humanoid Robots

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Abstract: In this review, we explore how teleoperation could potentially be applied to the management of humanoid robots, with an emphasis on humanoid robots that are used in assistive roles including clinical therapies and telemedicine. Since there are very few examples of teleoperation of a full humanoid, the review emphasizes those teleoperation technologies that are potentially relevant to the teleoperation of humanoids. Teleoperation of humanoid robots faces many of the same practical challenges associated with (a) traditional teleoperation, including latency and telepresence, and (b) teleoperating manipulators and other robots with high degrees of freedom. Teleoperation systems for humanoid robots must also address unique challenges triggered by strong emotional and social responses to humanoid robotics – responses of both the operator and any humans who may interact with the humanoid. These challenges trigger new opportunities for redefining teleoperation to include scripting, programming by demonstration, speech production, and Wizard of Oz interaction. The challenges also provide opportunities to specialize traditional modes of interaction and unique opportunities to develop humanoid-specific forms of teleoperation such as controlling humanoids via exoskeleton-based or inertial sensors. We include in this review a survey of enabling technologies, a taxonomy of practical uses, and a list of emerging themes and approaches to teleoperating humanoid robots.

Keywords: Teleoperation, humanoid robot, anthropomorphic robot, assistive robotics, therapy

I. INTRODUCTION

Teleoperation of remote robots and manipulators has been in use for decades, but the recent emergence of several types of humanoid robots provides an opportunity to reconsider teleoperation from a new perspective. Indeed, this is more than an opportunity for interesting research. It is necessary because, in practice, humanoid robots are often embedded in real physical and social environments and current levels of autonomy are insufficient to enable socially and physically competent humanoid behaviors. Including a robot operator dramatically increases the number of near-term uses of humanoid robots, spanning fields of remote medicine to socially assistive robotics.

Humanoid robots are being used in a lot of research projects and are rapidly approaching a critical time when they will either (a) start being used in real problems in the lives of real people or (b) fade away as a fad leaving the humanoid equivalent of an "AI winter" (Wikipedia, 2012a). Unfortunately, this chapter is not a survey of a broad set of existing systems, there are too few fully teleoperated humanoids, but rather a review and summary of how teleoperation has significant potential for improving humanoid robotics and increasing the scope of possible uses. The following use cases provide reason for optimism.

In February of 2011, the highly dexterous *Robonaut 2* robot, developed by NASA, went through a series of tests aboard the International Space Station (Melanson, 2012; NASA, 2012). Although one reason for sending Robonaut to the ISS was to test its capabilities, the costs of launching material into space is high enough that testing humanoids could not be the only or even the main reason for launching the robot. Two key reasons for sending Robonaut to the ISS include: First, Robotnaut can be a permanent resident without paying the price of human astronauts. Second, much of the ISS is designed to be used by humans; operation of levers, buttons, and knobs designed for humans are best manipulated by human-like appendages.

In contrast to using a humanoid to promote the goal of using space science, robots developed by Hiroshi Ishiguro and associates have been described as seminal to the new field called *Android Science* (Hornyak, 2006; Ishiguro, 2006). Androids are humanoid robots designed to be as similar to real humans as possible. Indeed, static images of robots like "Geminoid" are difficult to distinguish between real humans, though differences are currently apparent when these robots move or speak (Sakamoto, Kanda, Ono, Ishiguro, & Hagita, 2007). Developing human-like androids not only pushes the envelope in robot technology but also provides an avenue for understanding what makes us human and potentially provides insight into cognitive or social difficulties. In essence, androids may provide "an experimental apparatus that has the potential to be controlled more precisely than any human actor" (MacDorman & Ishiguro, 2006).

In contrast to making humanoids that look as much like humans as possible, researchers are making humanoid robots that are intentionally designed to not look too human-like. These humanoid robots may provide a valuable tool in providing *therapy for children with autism* (Barakova, 2011; Billard, Robins, Nadel, & Dautenhahn, 2007; Feil-Seifer & Mataric, 2008; Goodrich et al., 2012; Robins, Dautenhahn, & Dubowsky, 2006; Scassellati, 2005). These, and other humanoid robots, appear to trigger pro-social behavior in children with autism, behaviors that are non-existent or rare when these children interact with other children or adults.

Another example of a potentially useful human-controlled humanoid is the *MeBot*, which is a small humanoid "robotic avatar that gives a person a richer way to interact remotely with an audience" than could be achieved with conventional means (telephone or video conferencing) (Adalgeirsson & Breazeal, 2010; Breazeal, 2012). The idea is that a small robot is placed in, for example, a conference room and acts as a physical avatar for a remote human, allowing the remote human to use facial expressions and gestures to interact with others.

A final use case is using a humanoid to *assist people with every day manipulation* tasks, such as when a human has a physical or cognitive limitation that makes manipulation difficult (Adalgeirsson & Breazeal, 2010; Edsinger, 2007; Fan, King, Darb, & Kemp, 2010; Sokho et al., 1999). Humanoid robots in these uses, like the Robonaut, provide afforded behaviors that are tailored to household and other environments that are designed for humans and not for wheeled cylindrical or "tank-like" robots.

Although the morphology and application for each of these types of robot vary widely, each of the use cases shares something in common: all of these robots require and benefit from some degree of teleoperation.

II. TELEOPERATION AND HUMANOIDS

In this section, we discuss two aspects of humanoid teleoperation: (1) practices and technologies for supporting traditional teleoperation, and (2) extensions to the traditional notion of teleoperation. As we discuss these two topics, we emphasize factors that are unique to the teleoperation of humanoids.

A. Supporting and Applying Traditional Teleoperation

Teleoperation has, of course, been around for a very long time. Other chapters in this collection summarize the general history of teleoperation, so we restrict our discussion to two historical aspects that are relevant to humanoids: real-time operation and anthropomorphism.

1. Real-Time Teleoperation

Sheridan (1992) emphasized the real-time nature of teleoperation in his classic definition, "The term *teleoperation* most commonly refers to direct and continuous control of a [robot]" (p. 4 [emphasis in original]). The words "direct and continuous" mean that there is a real-time transference of human influence to robot behavior.

Real-time interaction brings with it a set of challenges that must be addressed to enable productive robot behaviors at a sustainable human workload. The first of these challenges is *latency,* defined as a time lag between when a human exerts influence and when the robot responds. All communication systems have some latency and even small delays can induce instabilities and oscillations (McRuer, 1995).

A second challenge is *situation awareness* (Endsley, Bolte, & Jones, 2003) or *presence* (Minsky, 1980). These phrases have different definitions, but we lump them together to emphasize that it is a serious challenge to rely on remote sensors to inform a human operator sufficiently so that he or she can produce effectual robot behaviors. Whether the solution is to ensure sufficient situation awareness so that the human can perform well or to ensure that the human feels "present" at the remote location, bandwidth limitations are often severe constraints on operation, even when sensors and sensor-processing algorithms are sufficient to theoretically support awareness.

2. Humanoids

Sheridan (1992) also identified issues associated with teleoperation of humanoids. He states, "An anthropomorphic robot has a human-like form, in that it senses its environment with what resembles eyes, manipulates mechanical objects with what resemble arms and hands, and/or moves in many directions with what resemble human body motions" (p. 5). Teleoperation of such robots requires the operator to "conceptually map its form and motions on his or her own body [via a] *physical alter ego*" (Sheridan, 1992, p. 5 [emphasis in original]). Much of the work on teleoperation discussed below focuses on the *physical aspects of teleoperation* such as retargeting from the human's morphology to the robot's (Dariush, Gienger, Jian, Goerick, & Fujimura, 2008) and the challenges of telemanipulation (Edsinger, 2007; Marayong, Bettini, & Okamura, 2002; Payandeh & Stanisic, 2002). Importantly, the sense of presence has been connected to the embodiment-related concepts of "morphology, body schema, and body image" that strongly affect how the sensor-motor channel operates (Haans & IJsselsteijn, 2012).

Recently, however, the social and emotional aspects of teleoperation have become more prominent. Although there are very specific physical reasons to focus on physical teleoperation (such as those associated with Robonaut [Ambrose et al., 2000] and manipulation support [Edsinger, 2007] introduced above), many emergent applications seek to apply the inherent socio-emotional responses of humans to humanoids (Barakova & Lourens, 2010; DiSalvo, Gemperle, Forlizzi, & Kiesler, 2002; Groom, Takayama, Ochi, & Nass, 2009; Lourens, van Berkel, & Barakova, 2010; Takayama, Groom, & Nass, 2009). Teleoperation of socio-emotional robots requires the operator to conceptually project his or her social or emotional intent into the gestures or expressions of the robot, forming a "socio-emotional alter ego." Importantly, socio-emotional responses to humanoids take place both with the operator and with those who interact with the teleoperated robot, creating a so-called "dual ecology" (Kuzuoka et al., 2004).

3. Beyond Real-Time Teleoperation

Building from the previous sections, we can offer the following definition:

> *Teleoperating a humanoid robot is the process through which a human directs remote sensors and manipulators using a communication channel subject to latency and bandwidth limitations in such a way that robot behaviors are physically, emotionally, socially, and task appropriate.*

Humanoids, which often have a very high number of physical degrees of freedom, inherit a huge number of potential behaviors that trigger social and emotional responses in humans.

Autonomy can help mitigate the huge challenges and complexities associated with teleoperating a humanoid, and many variations of and frameworks for autonomy have been developed (Bradshaw, Acquisti, et al., 2004; Bradshaw, Feltovich, et al., 2004; Crandall & Goodrich, 2002a; Hardin & Goodrich, 2009; Kaber & Endsley, 2004; Miller & Parasuraman, 2003; Miller, Funk, Dorneich, and Whitlow, 2002; Parasuraman, Sheridan, & Wickens, 2000; Sheridan & Verplank, 1978). These frameworks seek to shed light on the balance between authority and responsibility in human-robot interaction. The proliferation of frameworks indicates the richness of the problem of desiring appropriate autonomy as a way to assemble robot behavior and expressions into predictable, reliable, and useful quanta.

The definition for what is a useful quantum is rarely determined by a roboticist, and is dictated much more often by a non-roboticist in the form of a doctor, astronaut, therapist, teacher, caregiver, etc. (Yim, 2006). This has led to the development of what we call *offline teleoperation* wherein a non-roboticist programs the robot “between sessions” to create behavioral quanta that will likely be useful “within a teleoperation session” where the task is performed. In a way, offline teleoperation provides a way for a non-roboticist to perform so-called “Wizard of Oz” control before the robot goes online (Barakova, Gillesen, Huskens, & Lourens, 2012; Goodrich & Schultz, 2007; Green, Huttenrauch, & Eklundh, 2004; Huettenrauch, Eklundh, Green, & Topp, 2006; Kelley, 1984; Maulsby, Greenberg, & Mander, 1993; Molin, 2004; Riek, 2012). Wizard of Oz occurs when a person (usually the experimenter or a confederate) remotely operates a robot, controlling things such as its movement, navigation, speech, and gestures, etc., while the robot interacts with another human.

B. Supporting Teleoperation of Humanoids

Teleoperating a humanoid robot is difficult, but there are several reasons why teleoperation is currently necessary for humanoids. Perhaps most obviously, technology limitations require that a human be involved in robot behavior. Although progress continues to be made, there are limits to artificial intelligence and computer vision algorithms, including persistent challenges in (a) automatically recognizing objects and faces (Kang, Herbert, & Kanade, 2011; Zhao, Chellappa, Phillips, & Rosenfeld, 2003), (b) interpreting and understanding scenes and semantic spatial reasoning (Congcong, Wong, Xu, & Saxena, 2011; Kennedy et al., 2007), (c) prediction and planning, and (d) natural language understanding (Brick & Scheutz, 2007; Fong et al., 2006). Humans can often provide perception capabilities and strategic thinking that far exceed what can be provided by state-of-the-art algorithms. This is perhaps nowhere as blatant as when the humanoid is operating in a context where it is necessary to discern and respond to social cues (Kanda, Hirano, Eaton, & Ishiguro, 2004; Kanda, Shiomi, Miyashita, Ishiguro, & Hagita, 2010; Murphy, 2004; Tapus, Tapus, & Mataric, 2008).

Although accurate, this perspective motivates teleoperation as needed primarily because robots are deficient. There are positive motivations for using teleoperation that have very little to do with technological deficiencies. For example, in autism therapy, there is evidence that children with autism behave differently in the presence of a robot than in the presence of humans (Duquette, Michaud, & Mercier, 2008; Kozima, Nakagawa, & Yasuda, 2005a; Robins, Dautenhahn, te Boerkhorst, & Billard, 2004). Since the objective of the therapies is not to create a relationship between a child with autism and an autonomous robot, teleoperation of the robot provides an opportunity for a therapist or teacher to use the robot to catalyze interactions between the child and the human. As another example, ethical considerations in applications as distant from each other as elder care and military robots both suggest that using a human teleoperator instills a moral accountability that respects the sanctity of human life and human relationships (Arkin, 2008; Singer, 2009; Veruggio, Solis, & Van der Loos, 2011). Finally, there may be benefits to the human operator, such as when a scientist is able to gain insights into deep scientific processes by exploring the world in a hands-on fashion, albeit one where "hands-on" is mediated by a teleoperated robot. Planetary exploration and cell-level biology are two examples where the scientist may be benefited by the ability to teleoperate (Guo, Zhang, & Hata, 2002; Sun & Nelson, 2002; Spudis, 1992; Space Telerobotics (ANOTHER CHAPTER IN THIS COLLECTION); Ferketic et al, 2006; Hodges & Schmitt, 2010).

In addition to these direct benefits, an indirect benefit of teleoperation is that some operators prefer having direct control over delegating control to an algorithm or level of autonomy. This has been reported for expert teleoperators of remote vehicles (Marble, Bruemmer, & Few, 2003), though some experiments suggest otherwise (Bruemmer, Nielsen, & Gertman, 2008) and the reasons for acceptance and use may be complicated (Chambers & Nagel, 1985). There is reason to believe that some operators may prefer to directly control humanoid robots but that the reasons for doing so may be complicated.

Thus, teleoperation of humanoids is a technological necessity at this time, but it may also be a means for improving quality of life for certain individuals through robot-mediated assistance; we discuss this more in Section III. With this as the basis for the rest of the section, we first precisely identify several specific challenges associated with teleoperation, and then discuss technologies used to mitigate these challenges.

1. Specific Challenges

We consider three types of challenges: physical, socio-emotional, and operator-based. These challenges are summarized in Table 1 and described below.

Table 1. Challenges of teleoperation.

Challenge	Problem
Physical	• Morphology • Degrees of freedom • Dynamics • Sensors • Mobility and autonomy
Socio-emotional	• Social expectations of bystanders and patients • Ethics • Unintended communications • Motivation • Catalyst effects
Operator-based	• Skill and training • Mismatches between DOF and input modalities • Presence and situation awareness • Anthropomorphism by operator

Physical challenges are perhaps the most obvious obstacles and the ones that often receive attention by engineers, programmers, and roboticists. Morphologies, the physical structure of humans and robots, differ, requiring either the human or the robot to compensate for differences in reaching, joint movement, speed of operation, etc. Problems with morphology are exacerbated by the many degrees of freedom of the robot, making it complicated for a human to command all joint angles and actuators. Indeed, this is one reason why there are so few fully teleoperated humanoid robots. This can be made worse when, for example, the robot has multiple cameras or extra degrees of freedom (an elbow that moves backward, for example) that do not translate into a human's kinesthetic reference frame. The converse of having extra degrees of freedom is having limited mobility or autonomy, such as when a robot cannot reach the top of its head or grip a door handle while moving backward (Peterson, Austin, & Kragic, 2000; Petrovskaya & Ng, 2007).

The problem with degrees of freedom is further complicated by the requirement that the robot be statically stable. The robot Asimo from Honda, for example, can walk up and down stairs, but many approaches to footstep planning require that the robot stay balanced as it does so (Chestnutt et al., 2005). Humans, by contrast, maintain dynamic stability where at any given instance of time, stopping the swing of a leg or arm would cause the human to topple, but dynamically coordinating movements allows humans to move in something of a controlled fall. Coordinating degrees of freedom with different dynamic/static stability characteristics is a very difficult problem. This is exacerbated by the possibility that the robot is "under-sensed", meaning that the human operator cannot know for sure the precise angle of each joint or pressure on each appendage because the robot simply cannot sense these things in the way that a human can with his or her own body. Although adding autonomy can decrease degrees of freedom by coordinating degrees to produce coherent behavior, this introduces other challenges to the human who shifts from operator to manager or supervisor (Drucker, 1954; Sheridan, 1992; Sheridan & Verplank, 1978).

Socio-emotional challenges may be underestimated by roboticists, but receive considerable attention by social scientists and designers (e.g., Sung, Grinter, & Christensen, 2009; Forlizzi & DiSalvo, 2006; for socio-emotional issues associated with the Roomba® robotic vacuum cleaner). The emergence of socio-emotional challenges occurs when the humanoid robot, though remote from an operator, operates in an environment where other humans are present. Borrowing a term from Scholtz's taxonomy (Scholtz, Theofanos, & Antonishek, 2002), when a human is not directly involved in producing the behavior of the robot then he or she may be considered a "bystander." Additionally, in contexts of assistive robotics, the robot may be working with a client, patient, consumer, or visitor (Bolopion, Millet, Pacoret, & Regnier, 2013; Gockley et al., 2005; Goodrich et al, 2012; Kanda et al., 2010; Robins, Dickerson, Stribling, & Dautenhahn, 2004; Tapus, Tapus, & Mataric, 2009; Thrun et al., 1999). When humans are present with a humanoid robot, either as bystanders or in other roles (Goodrich & Schultz, 2007), these humans will experience socio-emotional responses to the humanoid. For purposes of this discussion, we refer to all such humans as bystanders/clients.

Humans respond in socio-emotional ways to robots (Groom et al., 2009; Reeves & Nass, 1996). These responses include expectations about how robots will behave, including respect for social distances (Dautenhahn, Walters, Woods, Koay, & Nehaniv, 2006; Mumm & Mutlu, 2011; Walters et al., 2005), predictability and trust (Short, Hart, Vu, & Scassellati, 2010; Roger, Guse, Mordoch, & Osterreicher, 2012), etiquette (Dautenhahn, 2007; Tsui, Desai, & Yanco, 2010; Walters, Dautenhahn, Woods, & Koay, 2007), and privacy (Syrdal, Walters, Otero, Koay, & Dautenhahn, 2007). Additionally, robot movements, gestures, or sounds, can convey unintended meaning to a bystander/client.

When properly managed, social and emotional responses can be very powerful, both as tools for motivation (Eriksson, Mataric, & Winstein, 2005; Tapus, Mataric, & Scasselati, 2007) and as catalysts for inducing desired/productive human-human behavior (Kozima, Nakagawa, & Yasuda, 2005b; Robins, Dautenhahn, & Dubowsky, 2005). Naturally, this power must respect ethical norms, including privacy, safety, trust, etc. (Syrdal et al., 2007; Veruggio et al., 2011).

These challenges are significant, but they say nothing about the additional limitations imposed by the *operators* themselves. There are wide variations in operator skills, including the ability to use technology, perform spatial reasoning, and convey intent (Chen & Barnes, 2008). Depending on whether the operator is an expert in controlling the robot such as with Robonaut or an expert in something else like science (Yim, 2006) or therapy (Barakova et al., 2012; Gillesen, Barakova, Huskens, & Feijs, 2011; Goodrich et al., 2012; Robins & Dautenhahn, 2006; Yim, 2006), the way of displaying or presenting information to the operator has a strong influence on how well the operator will be able to gain and maintain situation awareness or a sense of presence.

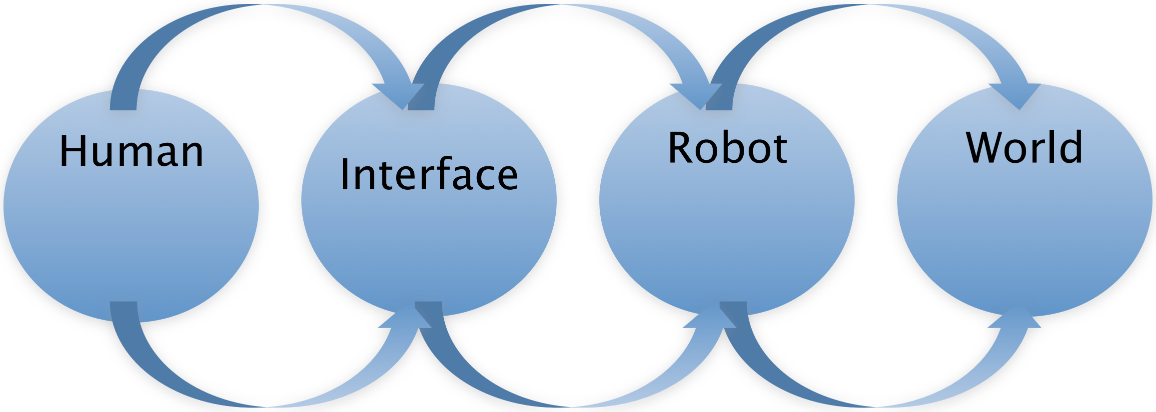

Figure 1. Robot-side versus operator-side approaches to improving teleoperation.

Similarly, the process and methods by which the operator issues commands to the robot will be differentially effective depending on the expertise and training of the operator. Finally, socio-emotional responses can occur in an operator just as they are invoked in bystanders/clients by humanoids. Indeed, even non-humanoid robots can trigger anthropomorphism, even under circumstances as trying as military operations (Singer, 2009).

2. Technological Solutions

We divide our discussion of solutions into two parts: robot-side solutions and operator-side solutions. Figure 1 illustrates who interacts with whom in remote teleoperation. Robot-side solutions occur to the right of the interface, and human-side solutions occur to the left of the interface.

Robot-side solutions take place between the robot and the world or between the robot and the interface. Solutions include improvements in sensors (touch, pressure, sound localization, vision, face recognition, etc.), improvements in mobility/expression (gestures, speech understanding and generation, facial expression, etc.), improvements in autonomy (planning, grasping, etc.), and advances in robot appearance (androids). Robot-side solutions are quite extensive and are best presented in a broader context, so we discuss those solutions in detail in Section II.C.

Operator-side solutions take place between the human and the user interface. Solutions can be clustered into sight, hearing, touch, and body-sensing technologies. Operator-side solutions are less extensive, so we summarize these solutions in the remainder of this section.

Sight and Visualization. With the growth of modern computing and graphical user interfaces (GUIs), a very common operator-side approach for improving teleoperation is to develop sophisticated GUIs. A typical GUI for a humanoid robot presents information obtained from the humanoid’s sensors in a visual format. Such information often includes video obtained from the humanoid’s camera(s), map information, information about the pose of the robot, and so-called “health” information such as the status of the battery or the efficiency of various sensors.

A challenge of using a conventional visual representation is that humanoids exist in the real three-dimensional world, so many techniques have been adapted to convey this to the operator. 3D visualization using some form of virtual reality (VR) is one way to do this (Goza, Ambrose, Diftler, & Spain, 2004), but multi-perspective displays and variations of VR such as augmented reality and augmented virtuality displays, which have been useful in vehicle teleoperation, may also be useful (Fong & Thorpe, 2001; Labonte, Boissy, & Michaud, 2010; Nielsen, Goodrich, & Ricks, 2007; Stone, 2000). When there are communication delays between the human and the robot, predictive displays are an important visual way for minimizing the impact of those delays both for manipulation and for vehicle teleoperation (Mehling, Strawser, Bridgwater, Verdeyen, & Rovekamp, 2007).

Hearing and Speech. Audio is another common approach for supporting a teleoperator. Audio can include all of the typical audio signals used in other human-machine systems including alarms and advanced versions of these systems such as binaural and stereo audio signals (Keyrouz & Diepold, 2007). Sometimes, audio signals are constructed by the user interface to help the operator maintain situation awareness, but audio signals can also be relayed versions of sounds picked up by the humanoid's microphones – something critically important for so-called "Wizard of Oz" teleoperation of robots (Glas, Kanda, Ishiguro, & Hagita, 2008; Green et al., 2004; Kanda et al., 2010). Sounds can also be used to enable a robot to attend to or track things in an environment (Valin, Michaud, & Rouat, 2007).

In addition to sounds from the robot's environments and sounds for promoting situation awareness, speech is another critical use of hearing. Speech is important enough and broad enough that it is treated separately from other sound-based methods for supporting an operator (Yokoyama et al., 2003). Speech-based elements of teleoperation include speech understanding/synthesis (Marin, Vila, Sanz, & Marzal, 2002), and scripted speech acts wherein the humanoid can be controlled by issuing speech commands (Lu, Liu, Chen, & Huang, 2010). Additionally, speech recognition, possibly supported by sound localization when environments are very noisy, can be used by a mobile robot to enable it to interact with bystanders or clients in the environment (Fréchette, Létourneau, Valin, & Michaud, 2012; Valin et al., 2007; Yamamoto et al., 2007).

Touch and Manipulation. A mouse is often a useful means for a human to communicate with a GUI and this is certainly true for vehicle teleoperation interfaces. However, the high degrees of freedom for humanoid robots make a mouse-based form of teleoperation less useful unless robot behaviors are assembled into pre-packaged behaviors (Goodrich et al., 2012). Joysticks or 3D mouses are a common alternative to conventional mouses and have been used in teleoperating humanoids (Neo, Yokoi, Kajita, & Tanie, 2007; Sian, Yokoi, Kajita, Kanehiro, & Tanie, 2002).

It is common practice to include some form of force feedback when teleoperating using joysticks for teleoperation. Conventional force feedback mechanisms can be augmented with more general forms of haptic-based interaction such as those used in robotic surgery (Beasley, 2012; Meenink et al., 2012). Haptic feedback need not be restricted to forces expressed through a joystick, but can follow patterns in vehicle teleoperation where haptic feedback can be given through the foot or other parts of the body. Additionally, there is work on conveying the feel for objects that a humanoid robot may be touching (Ambrose et al., 2000; Park & Khatib, 2006; Sokho et al., 1999), and there is evidence that tactile sensing by a robot can make robot reaching (and therefore teleoperation) easier (Jain, Killpack, Edsinger, & Kemp, 2012). Importantly, there is work on using haptic feedback from the patient or client side (Brokaw et al., 2011). We hypothesize that, from a patient point of view, there may be a haptic "uncanny valley" (Mori, 1970) for physical interactions with a robot, and this may be amplified by a mismatch between other humanoid characteristics such as morphology, movement, and social dialog. If this is true, than patient-side haptics will become more important as robots become more human-like.

With the emergence of tablet computers and smart phones, there are examples of vehicle teleoperation that use the touch-based metaphors used in these devices (Cummings, Fymat, & Hammond, 2012; Sakamoto, Honda, Inami, & Igarashi, 2009), but we know of no example of using these technologies for teleoperating a humanoid robot.

Body-Sensing Technologies. Although various forms of exoskeleton and body pose sensing have been around for a while, recent sensing breakthroughs have opened up many new opportunities for teleoperation of humanoid robots. Technologies for sensing the pose and movements of human operators include[1] vision (Moeslund, Hilton, & Krüger, 2006) and motion capture (Miller, Jenkins, Kallmann, & Mataric, 2004; Vlasic et al., 2007; Wikipedia, 2012c) including recent breakthroughs made possible by the affordable Kinect sensor (Vlasic et al., 2007). Vision-based methods are complemented by time-of-flight and other depth sensors (Dariush et al., 2008). These types of sensors lend themselves naturally to the detection of human gestures as a means for communicating with the robot via the user interface or directly, though other forms of gesture are possible such as using finger motions on a tablet to indicate a desired behavior.

Exoskeletons can be useful, especially when precise control of a specific manipulator is needed (Bergamasco et al., 1994; Koyama, Yamano, Takemura, & Maeno, 2002), and these exoskeletons can benefit from haptic and other forms of supported feedback (Letier, Motard, & Verschueren, 2010). Data gloves and tracking suits (Wousheng, Tianmiao, & Lei, 2003) can be thought of as types of exoskeleton in terms of the types of human inputs they afford, albeit ones that use different sensing technologies (Rani, Sarkar, Smith, & Adams, 2003).

Inertial sensing is often a part of exoskeleton and tracking suits, but inertial sensing is by no means limited to these types of input devices. Accelerometers and other inertial sensors abound on Wii remotes, tablet computers, and smartphones, and these can be used to control various platforms (Balakrishna, Sailaja, Rao, & Indurkhya, 2010; Quigley, Goodrich, & Beard, 2004; Walker & Miller, 2012).

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[1] This paper does not review futuristic interfaces such as completely immersive displays (e.g., those portrayed in the movie "Avatar").

Although the pose or movement of the physical body is important for controlling the high degrees of freedom of humanoids, there are other body-related sensing technologies that are also relevant. Of particular note are brain-machine interfaces, which are reviewed in another chapter in this collection [ANOTHER CHAPTER IN THIS COLLECTION]. These interfaces allow sensing of brain signals and their translation into movement commands for a robot. Other physiological sensors such as skin conductance can also be used to identify emotions or stressors on a human operator, allowing a robot to adapt to these important signals from the operator (Rani et al., 2003).

Multi-Modal Interactions. It is useful to note that it is unlikely that a single type of interaction style will be sufficient for all applications of teleoperation. Traditional multi-modal interfaces have been demonstrated (Perzanowski, Schultz, Adams, Marsh, & Bugajska, 2001), and interfaces that combine gestures, speech, and body references have also been created (Rogalla, Ehrenmann, Zollner, Becher, & Dillmann, 2002; Stiefelhagen et. al., 2004).

C. Extending Teleoperation

In this section, we review recent advances in robot-side technologies and features that have had an impact or are likely to have an impact on teleoperation systems for humanoid robots. These emerging robotic features allow users to more easily program and interact with robots. Additionally, these features have resulted in increased robot autonomy, which potentially allow operators to teleoperate humanoid robots more effectively by packaging commands and directives to the robot into small, but meaningful, quanta. Thus, after discussing robot-side solutions, we discuss methods for managing autonomous robot functions in teleoperation systems. We also discuss how many semi-autonomous robot functions can be combined in teleoperation systems to create full-body control. Finally, we discuss offline teleoperation, in which end-users create predefined robot behaviors customized to their anticipated needs.

1. Advances in Robot Technologies

Robot-side technologies include advances in both hardware and software. These advances include improvements in robot sensing (touch, pressure, sound localization, speech understanding, vision, object recognition, etc.), acting (mobility, gestures, speech generation, facial expressions, etc.), reasoning (planning, localization, grasping, etc.), and appearance (androids). We discuss each in turn.

Sensing. Robotic hardware for sensing has become both more capable and cheaper over time. While early robots relied almost exclusively on video data and coarse proximity sensors (such as sonar), today's robots are also often equipped with touch sensors, sound sensors, pressure sensors, high-accuracy proximity sensors (such as laser range finders), and sensors for determining the robot's current pose. The synthesis of these sensors allows robots to reason more effectively about their environment and to provide richer human-robot interactions with both operators and bystanders.

Equally important, advances in software related to sensor capabilities have made it so that robots can extract meaning from sensor data in order to sense the semantic environment. These technologies include sound localization (Hornstein, Lopes, Santos-Victor, & Lacerda, 2006), speech segregation (Roman, Wang, & Brown, 2003) and recognition (Anusuya & Katti, 2009), gesture recognition (Corradini, 2000; Stiefelhagen, 2004), object recognition (Roth & Winter, 2008), and scene understanding (Li, Socher, & Fei-Fei, 2009; Satkin, Lin, & Hebert, 2012). Thus, not only do robots have the ability to gather raw sensor data from the environment, but they can also reason about this raw data in order to sense the environment at a more meaningful level.

Action Capabilities. Both improved robot hardware and software have made robots capable of doing more things. From a hardware perspective, robots are becoming increasingly mobile, including navigation through unstructured terrain (Bermudez, Julian, Haldane, Abbeel, & Fearing, 2012; Wikipedia, 2012b) and running and fast walking (Boston Dynamics, 2012; Honda, 2012). Advances in mobility include humanoid-specific advances such as compliant interaction and variable based robots (Borst et al., 2009; Chen & Kemp, 2011; Ferland et al., 2012). Increased degrees of freedom in arms and hands have also made robots more capable of interacting through high-fidelity gestures and performing advanced tasks such as opening doors (Gray, Clingerman, Likhachev, & Chitta, 2011) and other forms of grasping (Sahbani, El-Khoury, & Bidaud, 2011). Enhanced facial features and speech generation technologies give robots the potential to engage in richer human-robot interactions. In short, advances in full-body dexterity means that operators can potentially use robots to do more things in teleoperation systems.

Reasoning. The capability to perform tasks does not, by itself, mean that robots will actually perform them correctly. From a software perspective, advanced reasoning is needed to reach this goal. While advanced robotic reasoning is still imperfect and failures often occur, a great deal of progress has been made on many fronts. Perhaps the greatest advancements have been made in localization and mapping (Montemerlo & Thrun, 2007) and in grasping (Sahbani et al., 2011). These and other autonomous algorithms can be leveraged by designers of humanoid teleoperation systems to augment traditional forms of teleoperation so that people can more easily control humanoid robots. We discuss methods for integrating such reasoning into teleoperation later in this section.

Appearance. The ability of a humanoid robot to interact effectively in assistive settings depends to some degree on its appearance. Many humanoid robots have become increasingly human-like in appearance (Ishiguro, 2006). For example, as indicated earlier, it is difficult to distinguish "Geminoid" (Sakamoto et al., 2007) from real people in static images. Increasing realism has a number of implications. First, this can allow robots to communicate more effectively via facial expressions and natural gestures. Second, when the robot's morphology is more human-like, the retargeting problem (morphing a human movements to the robot's movements) is easier. Mori's "uncanny valley" concept is a strong caution to the limits and challenges of increasing realism (Mori, 1970), and this might impose constraints on how and when a humanoid robot can be teleoperated.

2. Managing Robot Autonomy in Teleoperation Systems

The robot-side solutions that we have discussed do not, at least in the foreseeable future, eliminate or even necessarily reduce the role of the operator in teleoperation of humanoid robots in unstructured settings. Rather than eliminate interactions, Bainbridge (1983) noted that automation simply changes the nature of the human-robot interaction, sometimes in ways that add to its complexity. Thus, designers of humanoid teleoperation systems must determine how to effectively utilize robot-side enhancements while still providing operators with sufficient and appropriate control over the robot. Additionally, greater capacity in robot abilities leads to a greater desire for humans to use these abilities, especially for humanoid robots. Simply put, better robots can be used by humans to solve more important problems.

Table 2 enumerates methods introduced in the literature for managing robot autonomy in teleoperation systems. In this section, we review these, noting that these

Table 2. Methods for integrating robot autonomy into teleoperation.

A. Method	A. Description
Supervisory Control	One or more operators intermittently program the robot while receiving continuous information from the robot. The robot engages in closed-loop interaction with its task environment (Sheridan, 1992).
Direct Control	The operator manually controls the robot. No robot autonomy is used. *Mirroring*, in which the robot copies the human's movements, is a form of direct control.
Shared Control	The operator continuously provides input to the robot. The robot uses the input to generate a behavior by either following the operator's input strictly (as in direct control) or modifying it in some way to enhance performance or safety.
Traded Control	The operator initiates a task or behavior for the robot to follow, which the robot performs autonomously. The operator can stop the robot or initiate a new task or behavior at any time.
Collaborative Control	The robot and operator act as peers in determining the robot's behavior. "The human and robot engage in dialogue to exchange ideas, to ask questions, and to resolve differences" (Fong, Thorpe, & Baur, 2001).
Cooperative Control	Multiple operators cooperate to control a single robot via any of the above methodologies.

Table 3. Sheridan and Verplank's "Levels of Automation of Decision and Action Selection" (Sheridan & Verplank, 1978).

High	10. The computer decides everything, acts autonomously, ignoring the human
	9. informs the human only if it, the computer, decides to
	8. informs the human only if asked, or
	7. executes automatically, then necessarily informs the human, and
	6. allows the human a restricted time to veto before automatic execution, or
	5. executes that suggestion if the human approves, or
	4. suggests one alternative
	3. narrows the selection down to a few, or
	2. The computer offers a complete set of decision/action alternatives, or
	1. The computer offers no assistance: human must take all decisions and actions.

methods have not typically been developed specifically for teleoperation of humanoid robots, but have subsequently been used in humanoid teleoperation systems. These terms have not always been used consistently in the literature. Our classification is intended to simply describe the various methods that have been proposed for managing robot autonomy in teleoperation systems.

Supervisory Control. Supervisory control was defined by Sheridan (1992) as the process in which “one or more human operators are intermittently programming and continually receiving information from a [robot] that itself closes an autonomous control loop through artificial effectors to the controlled process or task environment.” In effect, in supervisory control, the robot’s autonomy is used to reduce the necessary input (and, hence, bandwidth) that the operator must supply to the robot so that the robot can perform the desired function.

The “intermittent programming” performed by the operator in supervisory control can vary considerably depending largely on the ability of the operator to communicate the desired function of the robot and the capability of the robot to perform that function. Sheridan and Verplank (1978) articulated the notion of a level of automation (LoA), which describes the role of the operator and robot in carrying out the task. In so doing, they enumerated ten example LoAs (Table 3), including full manual control, full robot autonomy, and everything in between. In Level 1, or manual control, the operator is fully responsible for the control of the robot. In the context of teleoperation, this is commonly referred to as direct control. In Level 10, or full robot autonomy, the robot operates without human input. At intermediate LoAs, the robot and operator share the responsibility for implementing the task. Popularly-used intermediate LoAs include management-by-consent (LoA #5), in which the robot plans a course of action and then asks the operator if it should carry out the plan, and management-by-exception (LoA #6), in which the robot plans a course of action and then carries it out unless the operator stops it within a certain time window.

While supervisory control coupled with the notion of levels of automation provides an umbrella for classifying methods to integrate robot autonomy into teleoperation systems, alternate terminology and control methods have emerged in the literature. Such methods include shared control, traded control, and collaborative control.

Shared Control. The term "shared control" refers to a teleoperation system in which the operator directs the robot's behavior via continuous input to the robot via the human-robot interface. However, unlike direct control, the robot can modify those inputs in order to meet the perceived system goals. The inference is that the operator is best at prescribing the robot's high-level behavior, but that the commands communicated by the operator might not lead the robot to behave as intended due to either the operator's inability to express the intended command or the operator's lack of telepresence and situation awareness.

A particularly salient example of shared control is called "safeguarding" (Fong, Thorpe, & Baur, 2001), in which the robot carries out the actions indicated by the operator unless the robot believes that those actions will violate some predefined safety goal, such as colliding into a wall or losing balance. Thus, in safeguarding, robot-side autonomy is used to augment human input so that safety standards are met without (ideally) compromising the operator's ability to effectively control the robot. In teleoperation of humanoid robots, safeguarding is a common practice for maintaining standing stability. For example, HRP-1S was programmed to ignore commands (by limiting joint angles) that could cause the robot to lose balance (Sian et al., 2002).

However, robot autonomy can also be used in shared control to derive robot movements rather than just veto unsafe movements. For example, Crandall and Goodrich (2002b) treated a trajectory communicated via a joystick as a high-level directive meant to specify the general direction a robot should travel rather than low-level command. Thus, upon receiving input from the joystick, the robot modified the joystick trajectory toward openings in the environment in the general direction of the operator's input. The resulting system substantially increased the system's performance while lowering the operator's workload. This latter form of shared control has also been used in the teleoperation of humanoids. For example, Neo et al. (2007) observed that operators have difficulty determining when to lift the robot's feet. To address this challenge, they devised mechanisms for autonomously shifting the robot's center of mass and autonomously adapting the robot's foot movements to ensure stability.

Traded Control. In traded control, the operator initiates a task (or subtask) for the robot to perform. The robot then performs this task until the operator stops it. In engaging in this method, the robot is assumed to be able to carry out the specified task without human input with some degree of reliability, but relies on the operator to determine what task the robot should perform. Given the difficulty of simultaneously controlling each of robot's appendages, traded control has become popular in teleoperation of humanoids (Lu, Huang, Li, Jiang, & Keerio, 2008; Rosenstein, Fagg, Platt, Sweeney, & Grupen, 2005; Sakamoto et al., 2007).

A salient example of traded control is *state-based control,* which was used to control the android Geminoid HI-1 (Sakamoto et al., 2007). In state-based control, the operator's role is to select the robot's state from a set of states. For example, Geminoid HI-1 had five conscious states (idle, speaking, listening, left-looking, and right-looking). A set of autonomous robot behaviors (or motion files) was defined for each state. Once the operator selected the robot's current state, the robot randomly selected and executed the motion files consistent with that state. This allowed the operator to control the robot's high-level behavior (by selecting states), but did not require the operator to individually control each of the robot's 50 actuators.

Collaborative Control. Direct, shared, and traded control are each master-slave interactions in which the operator is primarily responsible for defining the robot's goals and actions. When the robot has stronger goal-oriented reasoning, collaborative control can be used (Fong, Thorpe, & Baur, 2003). In collaborative control, the robot is treated as a peer rather than a tool. Thus, the authors argue that true collaboration means that the robot and human exchange ideas and ask each other questions to resolve any differences they might have in carrying out the desired task.

3. Integrating Multiple Semi-Autonomous Robot Functions

In manual teleoperation of humanoids, the operator must direct the movements of each of the robot's joints. The operator must control the head, arms, hands, legs, and torso simultaneously. Manually controlling any one of these appendages can be demanding with even the best interface technologies; manually managing all of them simultaneously is nearly impossible. In addition to attending to the low-level behavior of the robot, the operator must also be concerned about high-level tasks, including (1) portraying conscious and unconscious behaviors (Sakamoto et al., 2007) (2) navigating and avoiding objects, (3) understanding objects and scenes (Satkin et al., 2012) (Li et al., 2009), (4) planning a mission, and (5) interacting with people. Consequently, robot autonomy must typically be applied to many or all low-level movements while still providing the operator with sufficient control over the entire robot.

The movements of each joint of the robot can be managed by the teleoperator using any of the previously discussed control methodologies. Parasuraman et al. (2000) discussed how a different LoA could be used in each step of information processing, including sensory processing, perception, decision-making, and acting. Such processes are typically done in a serial manner. Higher LoAs can be used when the robot is capable of effectively performing a particular step of the process, while lower LoAs should be used in steps in which the robot has fewer capabilities.

Likewise, control of all of the robot's joints, which must be done in parallel, can also be implemented using a mixture of control methodologies. In this context, we are aware of three separate strategies from the literature for simultaneously operating all of the robot's joints. We name these three strategies *free control*, *point control*, and *plays and scripts* (Table 4). Since these strategies can likewise be used to manage multiple higher-level controls of the robot, we refer generically to each joint movement or high-level control process as a robot function.

Free Control. In free control, the operator simultaneously controls each robot function (or group of robot functions) independently. Each function can be implemented

Table 4. Three separate methods for controlling multiple robot functions in parallel.

Control Strategy	Description	Implications
Free control	The operator controls each robot function independently. Each function can be implemented with a different control method.	• High expressiveness; the operator can be given precise control over all functions of the robot. • Potentially high workload subject to the principles of fan-out.
Point control	The operator controls a single (selected) robot function or group of functions. The robot controls the other functions autonomously, consistent with the movements specified by the operator for the selected function.	• Expressiveness is governed by the power and relevance of the robot's control law to the desired task. • Potentially difficult for the operator to understand how inputs will affect all the robot's functions.
Plays and scripts	Pre-programmed behaviors for each robot function are packaged together *a priori*. A play is executed in run-time via traded control. A script is more interactive, in that it allows users to choose between multiple behaviors at choice points.	• High cohesion among the robot's various functions. • Expression during run-time is limited to what was envisioned before run-time; requires foresight about the tasks the robot will perform as well as the environment in which tasks will be performed.

with a different control method. Since the operator will need to neglect a function for periods of time while he or she attends to the other functions, the control methods used to control each of the robot's functions (or grouping of functions) should be chosen so that the workload of the subject is appropriately managed. Given that free control has many similarities with supervisory control of multiple independent robots (Crandall & Cummings, 2007), these control methods can be chosen according to the principles of neglect tolerance and fan-out (Crandall, Goodrich, Olsen, & Nielsen, 2005; Goodrich & Olsen, 2003; Olsen & Wood, 2004).

An element of free control was used in the control of the android Geminoid HI-1 (Sakamoto et al., 2007). While many of the robot's joints were controlled with state-based control (traded control), the lips and voice of the robot were controlled via mirroring (direct control), as a high degree of synchronization between lip movements and sound was required. Thus, the operator simultaneously controlled (a) the robot's movements (excluding the lips) via traded control and (b) the robot's lips and voice via direct control. This combination of control methods allowed the operator to more effectively control all of the robot's joints.

In free control, the operator has a high degree of freedom during run-time since he or she has some control over every function. On the other hand, this benefit is also a challenge and a risk as such freedom can cause the operator to experience high workload as he or she seeks to control and monitor all functions.

Point Control. In point control, the operator controls a single function or group of functions. Based on the behavior specified by the operator for this selected function, the robot autonomously controls the other functions of the robot. At the simplest level, the operator selects an appendage of the robot to control, while the rest of the body remains motionless. For example, Lu et al. (Lu et al., 2008) allow the operator to control either the hand or the head while the reminder of the body remains motionless. In other approaches, the movements of unselected joints are autonomously controlled so that the robot maintains its balance using inverse kinematics (Harada, Hasunuma, Nakashima, Kawai, & Hirukawa, 2008; Neo et al., 2007).

Another possible implementation of point control that has not yet been applied to teleoperation of humanoids is bio-inspired control, motivated by biological swarms such as ants and bees (Sumpter, 2006). In such swarms, simple control laws are used to defined each individuals behavior as it interacts with others. Biologically inspired methods have been used to teleoperate multi-robot teams (Goodrich, Sujit, Pendleton, & Pinto, 2011; Sycara & Lewis, 2012) and in producing biologically-motivated sensors and actuators (Sangbae et al., 2009; Shin, Sardellitti, Park, Khatib, & Cutkosky, 2010). Similar methods could potentially be used in teleoperation of humanoids by treating the various joints of the robot as independent entities that interact with connected joints. The operator could then potentially control a single segment of the robot (such as the hand) to prescribe full-body dexterity.

Point control can be a user-friendly method for teleoperating a robot since it only requires the operator to control a single aspect of the robot. However, this simplification also limits the expressiveness of the algorithm, making it subject to the constraints of the autonomous control law that controls the unselected functions of the robot.

Plays and Scripts. Predefined plays and scripts offer a third potential mechanism for operators to control all of a humanoid robot's functions simultaneously. The term *play* alludes to predefined methods for coordinating behaviors among members of a sports team. Likewise, in plays defined for a robot, behaviors for each of the robot's functions are pre-programmed and packaged together to create a whole-body behavior that the operator can initiate or terminate at any time. This methodology has been shown to be successful in the context of multi-robot teams (Miller et al., 2005; Parasuraman, Galster, Squire, Furukawa, & Miller, 2005). Scripts are similar, except that they provide the operator with the ability to select between multiple robot behaviors at choice points.

Since teleoperating the joint movements of humanoids in real-time is difficult, particularly with a mouse, keyboard, and joystick, plays have often been used in teleoperation of humanoids. Common plays for teleoperating humanoids include walking (Lu et al., 2008; Tachi et al., 2003) and grasping (Rosenstein et al., 2005).

Although plays and scripts are popular control methods for teleoperating humanoids since they facilitate user-friendly and simple interactions, they are only as effective as the foresight of the designer of the play or script. To design effective plays and scripts, one must know both the task that the robot must perform and the environment in which it must perform it. This severely limits the generalizability of plays and scripts, particularly since designers of plays for humanoids have traditionally been the designers of robot systems themselves. However, recent developments in offline teleoperation, in which end-users, who tend to know the tasks and environments, program their own plays, has great potential for overcoming this challenge (Barakova et al., 2012; Chaminade & Cheng, 2009; Feil-Seifer & Mataric, 2005; Goodrich et. al., 2012). This is especially true for humanoids, for which programming low-level autonomy through traditional means is particularly difficult.

4. Offline Teleoperation

Pre-programmed plays have traditionally been created by system designers who possess substantial technology expertise. These system designers carefully design autonomous robot capabilities to meet performance and safety considerations for the environments in which they expect the robot to operate. This design process typically involves time-consuming and awkward interactions with end-users, who are often domain experts with little technology expertise. Additionally, the resulting systems often fail in environments that differ even in small ways from those anticipated by the system designers. This awkward development cycle severely cripples the use of humanoid robots in the assistive settings discussed in Section III.

Offline teleoperation, the process in which *end-users program their own plays*, can potentially help to bypass this awkward and ineffective process. The goal of this process is to allow end-users to customize robot plays to their own circumstances. For offline teleoperation to be successful, two challenges must be overcome. First, since end-users do not typically have substantial technology expertise, traditional programming methods are impractical. User-friendly methods for programming robots in minimal time are needed.

A second challenge is that offline teleoperation does not easily facilitate performance and safety guarantees. End-users want to be able to quickly create plays “the night before.” They are not likely to carefully test their plays as is done in traditional design cycles. This can put the safety of both the robot and people at risk.

We are not aware of substantial work in facilitating performance and safety guarantees of humanoid behaviors created via offline teleoperation. However, there is a trend in current literature toward applying verification and validation methods to human-machine systems (Barakova et al., 2012a; Goodrich & Mercer, 2012; Rungta et al., 2013). The use of compliant mechanisms, force-limited actuators, and touch-aware autonomy may also help mitigate some of these challenges (Ham, Sugar, Vanderborght, Hollander, & Lefeber, 2009). Additionally, the ability to understand the robot’s computational processes and modify them in real time presents the possibility of dealing effectively with faulty robot autonomy (Harutyunyan et al., 2012).

However, a large body of literature is quickly developing on creating user-friendly programming methods using offline teleoperation. Four of these methods are

Table 5. Programming methods for offline teleoperation.

Programming Method	Interface Elements	Artificial Intelligence
Visual programming	-Desktop-style interface	Plays and scripts
Learning from Demonstrations	-Direct interaction -Direct physical interaction -Motion Capture	Recorded trajectories and/or keyframes
Learning from Reward	-Desktop-style interface -Speech interface	Reinforcement learning
Interactive Machine Learning	-Desktop-style interface	Classification algorithm

summarized in Table 5. Each programming method involves two elements: an interface element, which describes the communication between the human and the robot necessary to program (or teach) the robot, and the algorithms necessary to create the play.

Visual Programming. Perhaps the oldest method of offline teleoperation is visual programming (Burnett, 1999), a tool which is currently provided in programming interfaces supplied with many robots, including Lego Mindstorms and Nao robots. In visual programming, the user pieces together predefined (low- and high-level) sub-behaviors to form a complete play or script, which, for humanoids, specifies the movements of all the robot joints. This is traditionally done using a desktop-style interface in which the user drags and drops sub-behaviors and links them together. Links can be conditional based on sensor data obtained from the robot.

Learning from Demonstration. Another programming method that has gained a lot of attention in recent years is learning from demonstration (LfD). In LfD, the robot observes one or more demonstrations of the behavior from the user, and creates a behavior to imitate these demonstrations as best as possible (Argall, Chernova, Veloso, & Browning, 2009). LfD varies in many ways, including (a) how a user's behavior is encoded by the robot and then "played back" to the user, and (b) how the robot's "intelligence" is used to generate the robot's behavior from the user's input. For LfD applied to humanoids, the interface element may include one or more of the following: (a) computer-based interaction (Giullian et al., 2010), in which the user manipulates a 3-D representation of the robot on a computer screen to specify the trajectories or key frames of the robot's joints (Akgun, Cakmak, Yoo, & Thomaz, 2012), (b) kinesthetic teaching (Manohar, Marzooqi, & Crandall, 2011), in which the operator physically moves the robot to specify the robots movements (made possible by advanced sensor technologies), and (c) human motion capture (Moeslund & Granum, 2001; Vondrak, Sigal, Hodgins, & Jenkins, 2012; Yamane, Hodgins, & Brown, 2004), including gesture-based programming (Voyles, 1997).

The robot's level of intelligence is also critical to LfD algorithms. In the simplest case, the user's demonstration can simply be copied and replayed. In the case of computer-based interaction and kinesthetic teaching, the robot's joint movement must simply be recorded. In the case of motion capture, the user's movements must be retargeted to the humanoid to allow the robot to copy the user's demonstration (Dariush, Gienger, Jian, Goerick, & Fujimura, 2008). However, more sophisticated forms of LfD generalize the behavior to scenarios not previously observed (Argall, Browning, & Veloso, 2007; Calinon & Billard, 2009; Calinon, Guenter, & Billard, 2007; Vondrak et al., 2012). Such algorithms typically require the user to make multiple demonstrations of the task, and the robot generalizes the behavior to its current situation using some machine learning algorithm. Such techniques have great value in the context of humanoids where it is often extremely difficult to manually specify trajectories for all of the robot's joints.

Programming by Reward. Another method for programming plays for humanoids via learning is programming by reward (PbR) (Knox & Stone, 2010; Thomaz & Breazeal, 2008). In PbR, rather than provide the robot with exact body movements, the user observes the actions of the robot, and then rewards the robot for the actions it takes according to how successful the behavior is. The robot uses a classifier or reinforcement learning algorithm to create a generalized behavior from these rewards. Reward signals can be passed to the robot in any way, including speech or desktop interfaces.

For programming humanoids, PbR is particularly compelling since reward signals can be more easily conveyed than fully-body demonstrations. On the downside, humanoid robots have a very large state space, and hence humanoids typically learn quite slowly using traditional PbR techniques. Furthermore, the robot has the problem of finding good state features, though they can sometimes be extracted using LfD (Cobo, Isbell, & Thomaz, 2012).

Interactive Machine Learning. Finally, while many offline teleoperation programming methods have focused on programming robot trajectories, offline teleoperation methods also need to focus on being able to convey much more. For example, a humanoid may need to be taught to identify an object in the world, which could be embedded into a play in which the robot manipulates the object. One promising method for teaching a robot to identify objects (or recognize other important features that might trigger behaviors) is via interactive machine learning (IML) (Fails & Olsen, 2003). In IML, a human interacts in real-time with a machine learning algorithm to train a classifier. In essence, the human becomes a real-time data source for the classifier. The human provides data to the classifier, and then observes the data's impact on the classifier's outputs. This process is repeated until the human is satisfied with the classifier's outputs. Fails and Olsen (2003) showed that via a sequence of strokes in a camera image, a user can quickly teach a robot how to identify objects (contingent on color) in images using IML. Alternately, Chernova and Veloso (2008) developed an algorithm in which a robot recognizes what it does not know and asks for human training assistance.

III. Application to Assistive Robotics

Until relatively recently, robots were limited to industrial environments where precise manipulators were developed to automate dull, dirty, or dangerous tasks; and these robots only operated in environments where no humans were present or where human "communication" with the robots was limited to merely starting or stopping the robot. Recently, however, this has changed. The past few decades has seen a rapid increase in the research and actual use of robots in many areas, including (a) home assistance and care of the elderly and other general populations (Yan et al., 2012); (b) rehabilitation in physical therapies (Tapus, Tapus, & Mataric, 2009), such as stroke (Wade, Parnandi, & Mataric, 2011), cerebral palsy, multiple sclerosis, spinal cord injuries, and Parkinson disease (Krebs, Hogan, Aisen, & Volpe, 1998); (c) education for general knowledge and social skill development for children with autism; (d) search and rescue tasks, and (e) research and innovation, which we associate with the growth of applications for so-called knowledge economy.

In Section II of this review, we discussed how previous methods of teleoperation can be adapted to enable the teleoperation of humanoids, discussed humanoid-specific teleoperation modalities (e.g., exoskeleton), and discussed new concepts in teleoperation that mitigate some of the problems in the teleoperation of humanoids.

In this section, we review specific use cases for humanoid robots, emphasizing issues that arise in the teleoperation of these humanoids. We emphasize an important socially relevant problem that can benefit from the use of humanoid robots, namely social and assistive robots.

A. Overview of Social and Assistive Robotics

The field of social and assistive robots is an expanding research area that aims to find a solution to societal problems. These include (a) managing the needs of an aging society; (b) supporting practices that help provide for lower cost via remote and/or repetitive training in education and rehabilitation in home environments; (c) promoting practices that prevent health problems inherent in modern society and that motivate healthy living; (d) filling a deficit of personnel in education and training of children with special needs; and (e) mitigating the risks in search and rescue and space operations.

Robots in these domains have to operate in environments where humans are present, and these humans must often engage in direct and complex interactions with the robot. The tasks that robots can accomplish in such environments include physical support, shared task completion by a human and a robot, and interaction for purely social purposes. Robots performing these tasks often need to recognize and sometimes need to interpret human movements, facial expressions, and speech. Moreover, the robot may also be required to respond to or initiate social initiation.

Robotics that can operate under such conditions have been rightfully referred to as "new robotics" (Schaal, 2007); these new application domains require both a radical change in robot competencies as well as an expansion of the number of disciplines who contribute to development. More specifically, in social and assistive humanoid robotics, depth of knowledge and methodological sophistication in social sciences and psychology is as necessary as the mechatronics and algorithmic aspects of robotics. This is why Schaal claims that there is a global paradigm shift not only in the way that robots are used (Schaal, 2007) but also in the way that both new and old methods for designing, controlling and testing robots are applied.

This paradigm shift has fundamentally changed the teleoperation of humanoid robots. Although there is a common belief that teleoperation of robots will disappear with time, this has not been observed in practice. Rather, teleoperation methods have evolved new purposes and tools that match the novel needs of robotics, the novel research methodologies coming from the methodological toolboxes of social scientists and psychologists, and use cases that accompany a different, non-roboticist way of thinking.

B. Review of the State of the Art

We begin by identifying key features that characterize the problems in this application domain. These features determine the way in which teleoperation can take place. Although there are a variety of possible features, we emphasize the following: the *appearance* and complexity of the robots, the *environment* in which they operate, the *tasks* that the robots need to accomplish, and the trends in new technologies and materials used to perform teleoperation. As we discuss various applications, we describe application-specific teleoperation needs. Given these features, we identify and cluster several application domains based on their similarities with respect to the mentioned criteria. Results of this clustering are shown at the end of this section in Table 6. Before presenting the results, we provide more details about the features.

Robot Appearance. Although this paper emphasizes the teleoperation of humanoid robots, there are some specific human-like traits that are advantageous for each domain area. For instance, home assistance robots would typically have wheels to move faster and dexterous hands to handle objects, and they may be able to lift humans. Robots used in social training often need a more human-like appearance. They typically have legs and hands, but hand manipulation skills could be very basic. The appearance of the robot determines both the way in which teleoperation is performed and the range of technologies that can support teleoperation (e.g., motion-tracking suits may not suitable for controlling all robot morphologies such as robots that have wheels instead of legs*)*.

Environment. The environment for assistive robotics applications can have different degrees of "hostility" or difficulty. At one extreme, strictly structured environments may be used in physical therapy; at the other extreme, unknown, dangerous, or partially observable environments occur in rescue and space applications; and in between these extremes, dynamic and unstructured environments will occur in home assistance.

In addition to degrees of difficulty, the environment also includes the amount of technology used to create so-called ambient intelligence (AmI) (Saffiotti & Broxvall, 2005). In home environments, for instance, AmI might be used to support the robot or be supported by the robot.

Importantly, the environment can include a space in which the robot interacts with a human bystander/client, a domain specialist (in case of physical and social therapies), and a human operator. Dual ecologies (Kuzuoka et al., 2004) define two interaction environments that must be mediated and supported. This produces a wide range of "interactants", i.e. people with whom the robot must interact. This community of interactants may include engineers, designers, psychologists, social scientists, human-robot interaction specialists, teachers, therapists, health practitioners, and other domain specialists (Barakova et al., 2012; Huskens, Verschuur, Gillesen, Didden, & Barakova, 2013; Feil-Seifer & Mataric, 2005; M. A. Goodrich, Colton, M., Brinton, B., Fujiki, M., Atherton, J. A., Robinson, L., Ricks, D., Maxfield, M. H., and Acerson, A, 2012; Michaud et al., 2010). These different domain specialists come with different needs, ways of thinking (influenced by training and practice) and different methodological tools (Kim, Paul, Shic, & Scassellati, 2012). In addition, the development of internet technologies makes it possible for one or more interactant to be remote from the robot.

Often, it is useful to restrict this community to what we call a "dual user" problem: a *domain specialist* that uses the robot as a tool to augment his/her practice, and the *client or patient* that is traditionally served by the domain specialist and who is now (partially) served by a robot. These are typical in physical therapies and education of children with special needs (Huskens, Verschuur, Gillesen, Didden, & Barakova, 2013). Another example is the psychological/ sociological research domain where researchers often need to control the robot while exploring novel horizons. Here, Wizard of Oz scenarios are typical. A recent review on the use of Wizard of Oz techniques (Riek, 2012) gives a quantitative overview both within psychology and human-robot interaction.

Tasks supported. The term "tasks supported" refers to the types of tasks in which the teleoperation is needed to enhance the robot's performance. These tasks include physical assistance, monitoring, speech-based assistance, and assistance in decision-making. The range of tasks is domain-specific, and the levels and methods of teleoperation vary accordingly.

Teleoperation technology. Which teleoperation technology is best depends on the nature of the task, the need for precision, and the background of the interactants involved. For instance, domain specialists with no technical background need a user-friendly device, while a technically skilled teleoperator may be able to control a robot with newer, less-established technologies. Importantly, novel technologies provide novel opportunities for teleoperation as exemplified by the wide adoption of the Kinect sensor.

C. Teleoperation in Different Assistive Robotics Applications

Given the features discussed in the previous section, we are in a position where we can describe various applications and then organize these applications into several clusters. To facilitate an easy comparison of applications, these clusters are summarized at the end of the section in Table 6. We analyze the following applications: *physical therapies and neurorehabilitation*; *mental potential development* (autism, therapy, education, social companions; *elderly and home assistants*; *public spaces and open air applications*; and *research and innovation* (knowledge economy) applications.

Physical Therapies and Neurorehabilitation. (Table 6, first row). Historically, physical therapy and neurorehabilitation are the first application of robotics to an assistive domain. The robots used in these applications are traditionally static, they usually have a dexterous arm or leg used to support repetitive training, and they are not strictly humanoids (for a comprehensive review see (Krebs et al., 2008)). The physical therapies have been developed for specific patients groups such as stroke, cerebral palsy (CP), multiple sclerosis (MS), nontraumatic spinal cord injury (SCI), and Parkinson's disease (PD). In the more traditional use of the robots, the training session consists of a person that is physically connected to a robot that guides or augments the person's movement. The training is supervised by a therapist who may control the robot through an interface, and all robot programming is completed before the training has started. In this application there are two users, namely the therapist and the physically challenged person.

The tasks that robots can perform in physical therapies has been defined by Krebs et al. (1998) as follows: individually adjust the rehabilitative training protocol with due accuracy, replication, and congruity with residual motor function and treatment targets; quantitatively assess baseline conditions and monitor changes during training; acquire knowledge on motor re-organization; and extend applications with reduced costs by means of rehabilitative protocols performed at home under remote control.

Given this list of robotic tasks, we can identify the types of tasks that can potentially be supported by teleoperation. These include communication, motivation and practice with daily objects. Practice with everyday objects and tasks have been shown to be advantageous for recovering lost functions (Timmermans, Seelen, Willmann, & Kingma, 2009). Individualized rehabilitative protocols performed at home under remote control of an operator and combined with gradual adjustment of the level of training can be supported by teleoperation as well. The teleoperation technology used includes mainly (end-)user control interfaces, but alternative solutions are possible such as direct physical control facilitated by motion gloves and suits. In addition, game-aided approaches to rehabilitation have been used by (Andrade et al., 2010; Delbressine et al., 2012).

Recently, the field of rehabilitation robotics is moving beyond assistive technology that helps an individual *cope* with the environment to a new class of physically interactive, user-friendly robots that *facilitate recovery* (Krebs et al. 2008). In research environments, attempts to augment these therapies with socially assistive devices have been made. These include robots that have human appearance (Fasola & Mataric, 2012). In this new setting, the robotics task changes from a device that, for example, moves a human's hand to a robot that demonstrates the movement in front of a human and motivates the human to practice. With the introduction of such a motivator, the range of tasks that the robot can perform increases and, consequently, so does the complexity of the interaction.

At present, robots for physical therapy and rehabilitation operate in clinical environments. However, research studies are exploring possible domestic uses. A shift to domestic environments will give more opportunities for a person to engage in rehabilitation; this shift will also provide an opportunity to use the robot as a “persuader” in addition to its primary function of supporting physical exercise.

Importantly, this move from clinical to domestic environments has important implications for use; some of these implications will be seen in other applications as well. The first implication is that a therapist could be remote from the patient requiring the therapist to manage a robot that interacts with (and may be eventually controlled by) the patient. This is a fairly strong example of the dual ecology problem (Kuzuoka et al., 2004). The second implication impacts the required intelligence of the robot. The rehabilitation environment is highly constrained and robots do not need a level of intelligence required for the type of real-life applications. By contrast, domestic uses require significant improvements in the robot’s intelligence and autonomy.

Mental Potential Development. (Table 6, second row). There is a range of applications where robots are used to provide assistance to human users through social, rather than physical, interaction. These applications include social therapy for children with Autism Spectrum Disorders (ASD), education, social companionship, and social motivators. These applications have been collectively referred to as *socially assistive robotics* (Feil-Seifer & Mataric, 2005; Scassellati et al., 2012).

Typically, robots in socially assistive applications emphasize a human-like appearance and/or behavior. In the studies with children with ASD, there are different views on of how human-like the robot should appear. A robot that more closely resembles a human might make it easier for a child to generalize the social skills learned in human-robot encounters to human-human interactions (Lord & Bishop, 2010). The opposite choice, however, is motivated because less human-like appearance might (a) avoid overstimulation or confusion that may result from unnecessary details of movements and expressions, and (b) allow a designer or therapist to exaggerate social cues so they become more easily recognizable and generalizable. Robins et al. (2006) did a comparative study of the relationship between human-like appearance and child engagement, but much more work needs to be done to fully understand this for children with autism.

The human-like appearance of the robots in these applications enables the use of technologies that exploit the morphological similarities between the human teleoperator and the humanoid. These technologies include motion gloves, motion suits and exoskeletons. Learning by demonstration and other methods of performing offline teleoperation, as discussed above, are emerging in these applications, enabling a therapist to “program” the robot; these may be necessary for long-term therapies. In response to the need for a systematic way to create more sophisticated robot behaviors and perceptions, various authors (Barakova & Lourens, 2010; Lourens et al., 2010; Rett & Dias, 2007) have suggested using Laban movement analysis. Laban movement analysis links physical movement to the expression of a wide range of emotions, providing a potential means by which a therapist can teach the imitation of expressive signals. This is important for children with ASD because imitation training could facilitate understanding of social cues, as shown in the early studies of using robots for social training (Nadel, Revel, Andry, & Gaussier, 2004; Robins at al. 2004).

Shifting from understanding and generation of social cues, it has been observed that training purely motor skills to children with autism may result in better social behaviors later in life (Barakova & Chonnaparamutt, 2009; Leary & Hill, 1996). The benefits from robot-assisted training have been reported for a set of motor skills that are basic to social behavior. These include imitation (Nadel et al., 2004), eye contact, and joint attention (Kozima 2006, Robins at al. 2004), grasping (Barakova & Chonnaparamutt, 2009; Sutera et al., 2007), and turn-taking (Brok, 2010). These results indicate that training motor skills is a promising area of research on the use of robots in autism therapy.

The latest trends in using robots for social therapies and education include not only the recognition of facial expressions but also verbal interaction between the robot and the children, both of which have successfully been trained with robots. At present, such interactions are restricted to scripted dialogs that might need to be redirected to different branches of the scenario depending on the answer of the trainee or client (Diehl et al. 2011; Huskens, Verschuur, Gillesen, Didden, & Barakova, 2013). Despite these limited successes, there remain serious challenges to training speech interaction. First, speech recognition is still one of the most difficult problems for AI research. Second, the verbal utterances of children with disabilities may not even be understandable for another human, making the performance of speech recognition algorithms woefully inadequate. Consequently, many therapy applications involving speech are controlled remotely through a Wizard of Oz teleoperation (Riek, 2012).

Wizard of Oz teleoperation is also used in other therapy applications, particularly those in which it is desirable for the robot's behavior to be as flexible as possible, limited only by the human controller's skill and the robot's capabilities. Teachers and therapists in special education need to be able to initiate, terminate, and interrupt scripts, either to manage the contingencies that arise in therapy or to protect the child or robot from harm. In these applications, the robot may be teleoperated either by an experimenter who has no role in the interaction scenario or by a therapist/teacher who is a part of the interaction. Interfaces to support these types of Wizard of Oz interactions can include a "whole-world" view of the interaction environment (Kozima et al., 2005a) or only that portion of the world visible through the "eyes" of the robot; this latter type of interaction may support a more natural interaction but at the cost of increased operator workload.

In the future, the study of teleoperation of social assistants should focus on understanding more of the context of the interaction. Using domain professionals to direct the course of interaction through an appropriate teleoperation interface is a solution that is currently being implemented in several ongoing projects.

Elderly and Home Assistants. (Table 6, third row). The aging society is seen as a world-wide problem in developed countries, and there is a lot of research funding available to address home assistance for elderly care. As a result, there are many ongoing robot-based projects for providing elder care including CompanionAble[2], MobiServ[3], Domeo[4], and KSERA[5]. These projects work towards integrating robots into home environments to provide support for elderly or impaired persons who are living independently at home.

To date, the robots developed for elderly and home assistants have usually been wheeled robots with upper bodies that have dexterous hand(s) and a screen for interaction, although several robots have been developed to have more human-like upper bodies. The robots are usually built so that they can provide physical assistance including retrieving and delivering objects (Bera, van Hee, & van der Werf, 2012) or even lifting people (Mukai, Nakashima, Sakaida, & Guo, 2011). For both safety and ethical reasons, tasks such as lifting a person currently require a human teleoperator. Delivering objects also currently requires teleoperation, not because of ethical reason but rather because of the low reliability of state-of-the-art object recognition and grasping algorithms.

Elderly and home assistance robots operate in unstructured, changing, and possibly dynamic environments where people and objects may move freely. In addition, the robots and teleoperation interfaces for this application area must be able to support a large variety of users while assuring that the overall system is affordable. The home environment may be instrumented with sensors and algorithms, creating a so-called ambient intelligence environment (AmI) that may help the human teleoperator and/or the robot in their assistance tasks.

The majority of the ongoing projects on home assistance robots report similar challenges and insights arising from training and evaluation with end-users. One typical challenge arises from the perception that the assistive robotics platforms have low reliability. This has a direct impact on human perceptions and preferences. For example, Torta, Werner, Cujipers, and Juola (2012) show how people perceive a robot as a better motivator than standard domestic interfaces, but still prefer standard interfaces for urgent communications. This finding suggests that users may feel comfortable with a robot in their home if they are aware that a human teleoperator is available to manage the robot when conditions are critical and the system needs to be highly responsive.

Research on improving the physical and social capabilities of home assistance robots is ongoing. Yan and colleagues (Yan et al., 2012) provide a comprehensive discussion of the artificial intelligence techniques that enable a humanoid robot to address a person in an ambient assisted living environment (smart home). These authors show how localization, spatial navigation, face detection and head pose estimation can be integrated together, and they also emphasize just how complex it is to achieve the important task of properly addressing a person. They conclude that, at present, the ambitions of artificial intelligence have to give space for combination of the robot intelligence with the

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[2] http://www.companionable.net/

[3] http://www.brl.ac.uk/researchprojects/mobiservproject.aspx

[4] http://www.aal-domeo.eu/index.php/robots

[5] http://ksera.ieis.tue.nl

opportunities provided by teleoperation. Complementing these technology-driven justifications for teleoperation are ethical considerations about the moral responsibility and accountability of using robots to provide care for vulnerable portions of the population (Sharkey & Sharkey, 2012).

Because the ratio of elderly persons to young persons is growing, solutions are sought that will allow a single remote teleoperator to provide support for several elderly people located at different locations. This raises a range of novel research problems such as helping the robot to identify and grasp the right object in the particular home. Bera et al. (2012) demonstrate shared control on a teleoperated robot named ROSE, where the robot is able to perform tasks autonomously, but the human operator is always able to take over control from a cockpit. The authors address problems that are typical for distributed systems that communicate asynchronously (i.e. by message passing) and propose a systematic way to design such systems such that certain behavioral properties are guaranteed by construction.

Research and Innovation (Knowledge Economy). (Table 6, fourth row). The research and development community is by far the most frequent user of assistive robots at present. This trend, of researchers and engineers developing new technologies, is common in many developed countries, and is recognized as a novel branch of industry called the "knowledge economy." As exemplified by the development and adoption of smart phones, it is evident that research development and innovation cycles are shorter and and more profitable than many traditional products.

Knowledge economy workers in the field of robotics include researchers from universities and other institutions, but many companies are also developing applications with robots: iRobot[6], Fraunhofer[7], Sony[8], Philips[9], Willow Garage[10], Aldebaran[11], and TiViPE[12], to name but a few. Interestingly, sales of the AIBO robot by Sony, the iCat robot by Philips, and the Nao robot by Aldebaran have primarily been to researchers. These sells pave the road for newer robotics companies to potentially work with domain specialists to co-develop robot applications for the uptake and the actual use of the robots in practice.

Multidisciplinary efforts to develop innovative robot applications with foreseeable returns has brought together mechatronics specialists, computer scientists, social scientists, psychologists, neuroscientists, human-robot interaction specialists, designers

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[6] http://store.irobot.com/

[7] http://www.iais.fraunhofer.de/

[8] http://www.sony.net/SonyInfo/CorporateInfo/History/sonyhistory-j.html

[9] http://www.research.philips.com/technologies/projects/robotics/

[10] http://www.willowgarage.com/

[11] http://www.aldebaran-robotics.com/en/

[12] http://www.tivipe.com/index.php?option=com_content&view=article&id=67:controlling-robots-within-tivipe&catid=49:robotics&Itemid=82

and professionals from innovation sciences together with specialists from the application domains, i.e. therapists, teachers, etc. Each community of researchers or practitioners comes with its own perspective on how robots might be useful. Each also brings its own methodologies and requirements for the use of robots and for the control that humans need to have in this process.

A long-term expectation of some individuals is that autonomous and self-aware robots will be integrated in our society, and that these robots will support humans in different situations. This implies that robots need to interpret, adapt to, or even emulate human intelligence. Teleoperation and remote control of such robots is generally seen as a setback, or as an intermediate solution towards inherently intelligent robots that is just slightly out of reach given our present knowledge and engineering capabilities. Anecdotally, this view is especially popular among robot researchers who have mechatronics and computing science backgrounds, largely because these researchers want to further improve mechanical, material, and computational features of the robots. Since this group of researchers often gets more involved in application-oriented multidisciplinary projects, they are seeing research opportunities in formalizing the protocols for teleoperation. The question of how a human user and a robot should collaborate during teleoperation has been approached by Dragone, Holz, and O’Hare (2007) and Sandygulova, Campbell, Dragone, and O'Hare (2012).

It appears that many researchers and developers develop technological solutions needed in a broad range of novel applications without focusing on specific application domains. Such developments are based on the miniaturization and omnipresence of technology, global connectedness, new materials, and societal trends such as the massive use of social media, relocation of health, education, and other services to homes, using local and online communities to support the teleoperation of robots.

By contrast to technology-driven innovations, other researchers are directly motivated by the needs of humans and how robots can be used to fill these needs in present-day society. This group of specialists searches for the opportunities that the developments in science, technology, and society provide for the use of teleoperation in innovative and empowering ways, including using robots to augment life rather than just to replace some missing functionality.

Importantly, there is another group of researchers who seek to use robots not to fulfill a specific need in society but rather to develop a deeper scientific understanding of basic human traits. Researchers in humanities and neurosciences see opportunities to use (teleoperated) robot technologies to simulate and study aspects of human behavior such as perception, embodiment, and presence. Robots are embodied but still allow for controlled variation in their appearance and behaviors. Because these variations can affect the perception and the feeling of presence of another intelligent or emotional creature, robots have been used to test cognitive theories and neuroscience hypotheses. For example, Chaminade and Cheng (2009) argue that because humanoid robots reproduce part of the human appearance, they provide a testbed for hypotheses pertaining to natural social interactions. This perspective has been noted previously in this chapter as a stated objective for the field of android science.

In this research area, robotic experiments could (but do not necessarily) involve modeling of natural (human) intelligence (Trafton et al, 2006; Brick & Scheutz 2007). Some authors argue that the previous approaches that claim to focus on biologically inspired behavioral actually had little direct input from biological sciences. These authors further argue that a more direct connection between humanoid robots and social cognitive neuroscience has to be sought through the motor resonance paradigm, which is a paradigm is largely based on the discovery of the mirror neurons that appear to be a key biological basis of social interaction. Several studies (Barakova & Feijs, 2011; Chaminade & Cheng, 2009; Metta, Sandini, Natale, Craighero, & Fadiga, 2006) formalize the need of robotics in neuro- and cognitive sciences in terms of understanding imitation, synchronization of social gestures, and social learning within the mirror neuron framework. These authors search for direct ways for the robot to learn, adapt and interact. Extending beyond these studies, the mirror neuron paradigm may give insight into novel ways to teleoperate the robot, since learning by imitation in robots is a mechanism that gives more possibilities than learning by demonstration. The mirror neuron paradigm can thus offer unexplored possibilities for a more natural interaction and teleoperation than kinesthetic teaching.

Robot Assistants in Public Spaces. (Table 6, fifth row). Field trials of robots placed in real-life public space environments such as museums, shopping malls, and train stations, have shown encouraging results. Indeed, robots have served as museum guides for over a decade (Burgard et al., 1999) These robots have often been wheeled and interact through a screen interface, but speech-based interactions are also being developed. The environments in which these robots operate can be classified as "partially conditioned" because the designer has some control over the environment (e.g., the locations and types of objects and features of the environment) but not total control.

A comprehensive overview of using mobile robots as tour guides in expositions, and museums is given in (Jensen et al., 2005). These robots guide visitors to a set of predefined exhibits following a planned path while offering exhibition-related information. They navigate in populated, but completely known environments, but these environments are much more dynamic than home environments because multiple humans can move freely in expositions and museums. A key need for autonomous navigation in such dynamic environments is the further development of efficient autonomous navigation algorithms such as SLAM (Smith & Cheeseman, 1986).

As a complement to the design of museum guide robots, there is work on developing shopping assistant robots. Shopping assistant robots have to meet more challenging demands than museum robots since they have to navigate in less controllable environments following previously undetermined routes and performing challenging tasks such as picking up an object. For these increased requirements, partially or completely teleoperated robots have been developed (Glas, Kanda, Ishiguro, & Hagita, 2012). In addition to combining different motor tasks such as navigation and object grasping, shopping robots must address the important problem of how a robot can approach the human and how this encounter could evolve in useful interaction. Solving this problem remains challenging and requires a level of autonomy and intelligence that requires additional advances in artificial intelligence.

Shifting to another challenging problem, there is a need for robots to involve humans in more complex and natural interaction by properly approaching a person and having a simple conversation (Shiomi et al., 2009; Weiss et al., 2010). Studies of shopping mall applications in Japan (Shiomi et al., 2009) have shown that the ability of robots to "understand" natural language is a very desirable feature for humans who occupy public spaces, particularly when humans are waiting for their turn to interact with the robot. Importantly, it is not clear how fast humans' fascination for robots will settle down if the robots were omnipresent, and if the robot had to indeed perform an assistive function, but it is likely that the ability of the robot to engage in natural dialog will be crucial. At present, similarly to other application domains, dialog of a robot in a shopping mall is performed by Wizard of Oz teleoperation.

There is a clear trend in this application domain toward multiple users and multiple robots. The problem of controlling a team of robots poses new challenges for teleoperation (Glas et al., 2008). These authors expect that with the increase of robotic technology, and accordingly their autonomy, one teleoperator will be able to control multiple robots. They introduce the operator-to-robot ratio as a measure of robot autonomy and outline the present day problems of multiple robot teleoperation. The teleoperator in this application domain must perform a dual task: monitor all robots and identify situations in which his/her assistance is needed, and be able to assist an individual robot in a specific situation even if the set of robots has a high degree of heterogeneity. The teleoperation technologies, in addition to a GUI that enables an operator to control one robot at a time while monitoring several others in the background, include a control architecture that enables the scripting of conditional behavior flows for social interaction. In these applications, the timing and delays in interaction play pronounced roles. Distribution of attention to the most demanding task and smoothly interleaving the demands of multiple robots have been addressed by (Glas, Kanda, Ishiguro, & Hagita, 2012).

Table 6. Categorization of applications and domains for teleoperated robots. (Index of abbreviations: CP = Cerebral Palsy. MS = Multiple Sclerosis. SCI =Spinal Cord Injury. PD = Parkinson's Disease. AmI = Ambient Intelligence. LbD = Learning by Demonstration. ASD = Autism Spectrum Disorder. WoZ = Wizard of Oz.)

Application	Appearance	Users	Environments	Tasks	Technologies
Physical therapy	Parts of or a complete humanoid body	•Patient groups: stroke, CP, MS, SCI, PD •Therapists	•Clinical & other preconditioned environments •Home environments with AmI	•Training/ assistance of repetitive movements •Physical assistance •Monitoring •Motivation	•Remote manipulation •LbD & offline teleoperation. •Motion suits •Exoskeletons
Mental potential development	•Human-like appearance •Gestures and simple facial expressions	•Children with ASD •Typically-developing children •Elderly •Therapists	•Clinical environments •Home environments	•Speech and movement-based interaction •Therapist/ teacher initiates, terminates, and directs scripts	•End-user interfaces for creating and controlling scripts •LbD & offline teleoperation
Elderly and home assistants	Wheeled robot with human-like hand(s)	•Elderly •Everybody	•Home (AmI) environment •Care centers	•Monitoring •Physical assistance	•Remote navigation & manipulation •Motion gloves and suits • WoZ
Research and innovation (knowledge economy)	Humanoids Androids Others	•Application specialists •Designers •Innovation sciences	Preconditioned environments	•Nonverbal, physical and speech interaction •Multi-tasking, timing and parallelization	•LbD & offline teleoperaiton •Motion suits •WoZ
Public spaces and open air applications	Wheeled robot with human-like upper body	Everybody	•Highly dynamic environments • Unstructured environments	•Navigation •Speech-based assistance •Initiation of social interaction	•Remote navigation assistance •Remote conversation assistance

IV. Conclusions

Because of the complexity of teleoperating the many degrees of freedom of a humanoid robot, a complexity amplified by the need to honor physical, emotional, and social constraints, there are very few examples of completely teleoperated humanoid robots. There are, however, many emerging technologies and solution approaches that can support near-term and far-term applications that use teleoperated humanoids for managing, creating, and shaping human-humanoid interactions. In this concluding section, we summarize a set of common solution themes and add a set of open challenges that must be addressed.

A. Common Solutions

In this section, we summarize three common solution themes described in this chapter. First, we explore the impact of the dual ecology of human-humanoid interaction. Second, we explore methods and impacts of incorporating autonomy into teleoperation. Finally, we discuss the importance of integration in designing functional systems.

1. Dual Ecology

The first set of common solution approaches center around the concept of the *dual ecology* created because humanoids interact with both an operator and with other humans including patients, clients, and bystanders (Kuzuoka et al., 2004). Figure 2 illustrates three agents: operator, humanoid, and another interactant. The humanoid and the interactant will interact with each other and with the robot. The operator's goal is to facilitate these interactions by influencing or controlling the behavior of the humanoid. This task is extremely difficult since the operator may need to simultaneously interact with both the robot and the interactant, as in using robots to support, for example, autism therapy, stroke rehabilitation, and cerebral palsy therapies. In these types of use cases, the operator must focus primary attention on the therapy rather than trying to coordinate several degrees of freedom of a teleoperated robot. Even telesurgery will likely include interactions between a remote surgeon communicating via voice with an assistant that is present in the room with the patient.

Simply put, dual ecology impacts almost every aspect of designing teleoperation for humanoid robots: the robot's physical appearance (human-like or intentionally unlike a human); the means of communicating; the design of interfaces that respect physical, mental, and social demands placed on the operator; the socio-emotional state induced in both operator and interactants by robot behavior and reliability; the possibility of non-experts operating the robot; and the likelihood that the robot will operate in an unconstrained environment.

This leads to the natural conclusion that, from both operator and client perspectives, personalization matters. This is manifest in things as simple as robot appearance (Sung, Grinter, Christensen, 2009) as well as in the need for personalized robot behaviors. From the client side, personalization may be controlled or influenced by the robot handler, or may happen as a result of the interaction between client and robot algorithms. From the operator side, personalization naturally includes the ability to adapt robot behavior to suit the needs of the problem holder, but may also include modifying tools to program robots (see Table 5), to control robot behaviors (see Table 4), or to select a method for integrating robot autonomy into teleoperation (see Table 2).

A broader manifestation of the dual ecology occurs when we note that human-humanoid interaction is embedded within a climate of sensitive cultural and ethical issues, especially on the client side. There are cultural differences in how people perceive, interact with, and accept robots (Bartneck, Namura, Kanda, Suzuki, & Kato, 2005; Kaplan, 2004). Ethical issues include physical and psychological safety (Kamide et al., 2012), responsibility and accountability for potential robot-induced harm (Arkin, 2008; Veruggio et al., 2011), and the long-term societal impacts of involving robots in eldercare, nursing, and other environments with vulnerable populations (Sharkey & Sharkey, 2012). Humanoid robots, with their potential for engaging deep emotional and social human responses, must directly address cultural and ethical issues.

Although not discussed in the body of the chapter, it is useful to note that insight into the dual ecology can be derived using the implicit roles of *problem holder* and *stakeholder*, defined by Woods et al. (Woods, Tittle, Feil, & Roesler, 2004). The problem holder is the one who is responsible for shaping interactions in such a way that some mission or objective is accomplished. The stakeholder, by contrast, may have less influence over how interactions are shaped but may still have a vested interest in the outcome of the interactions. These implicit roles are dissimilar from Scholtz's roles (and variants) for HRI (Goodrich & Schultz, 2007; Scholtz, Theofanos, & Antonishek, 2002) in that they do not define a particular division of tasks or authority but rather make explicit the fact that different humans care about and invest in robot behavior in different ways and at different levels. This requires us to apply the lesson from (Woods, 2004) and design systems that support "people in their [different] roles."

2. Autonomy

The second set of solution approaches results from the need to find a balance between robot autonomy and human teleoperation. The high degrees of freedom for a humanoid robot and the broad set of socio-emotional/physical interactions resulting from the dual ecology make it nearly impossible for a single human to operate the robot. The standard solution to this problem is to introduce algorithms that create behavioral or perceptual quanta, and then require the operator to manage these quanta.

The key ideas of moving beyond traditional teleoperation are to assemble robot behaviors into behavior quanta that can then be sequenced or activated as needed during a teleoperation session.

This shifts the operator's responsibility from one of real-time teleoperation to designing, managing, and shaping behavioral and perceptual quanta. Simply put, the operator becomes a manager and creator of autonomy.

This brings additional complexity in the task of the operator, and therefore calls for reducing the overall complexity of teleoperation task. For instance, in behavioral therapies the therapist-teleoperator was previously focused on the responses of the child and now may have to manage the robot responses in addition. Therefore, although from the perspective of creating autonomy, physical interaction between a human and robot affords opportunities for programming robot behaviors and invoking useful social responses in humans, this type of robot "programming" is susceptible to the theoretical limitations associated with any form of teleoperation. Moreover, it is not immediately obvious how the physical activities of the human programmer will induce social responses in other humans who may be stakeholders in the interaction. This limitation can be generalized for other forms of programming by demonstration, either through physical interaction or imitation. Even though the general idea of programing by demonstration provides an important way for humans to naturally convey intent to robots without requiring low-level programming, there are still open question about how to deal with theoretical limits in expressiveness and practical limits of induced social responses.

Moreover, the operator will typically have programmed or scripted robot behaviors *a priori*, so immediate interactions are constrained or at least strongly influenced by previous interactions. This may be deliberate, such as when a clinician programs a set of behaviors to support a therapy plan, or inherent, such as when the robot has memory or is capable of learning from previous experience. Since the operator will learn, prior experience will undoubtedly influence the interaction between humanoid and operator, sometimes producing higher efficiencies but sometimes discounting potentially useful or productive interactions. In addition, the term "therapists" is used in robotics literature as an umbrella term, covering actual therapists/psychologists who create the training programs, and trainers who actually perform the training, but are not involved in the design of the therapy. Often the teleoperator is the trainer, who did not program or took part in conceptually programming the robot interaction; see, for example, (Huskens, Verschuur, Gillesen, Didden, & Barakova, 2013.

Assuming that behavioral quanta can be created, scripting, choreographing, scaffolding, and other teaching/organization metaphors provide potential for sequencing behavioral quanta into a suite of potential behaviors that can be used to support powerful and long-term interactions. Much work needs to be done to understand the proper construction of behavioral narratives that can evolve under triadic client-manager-robot interactions subject to some sort of mission or session objective. In essence, this problem is to find a way to connect online and offline teleoperation by managing the temporal evolution of teleoperation in the presence of programming, interaction, and learning.

3. Integration

The third solution theme is that managing a set of perceptual and behavioral algorithms in a dual ecology setting requires the integration of multiple design elements. For example, there are three technologies that seem to be emerging as being effective for managing teleoperation: body-based teleoperation, graphical user interfaces, and multi-modal displays. Realistically, future user interfaces are likely to require an integration of one or more of these elements, exploiting as many interaction channels as possible.

Importantly, work emerging from the authors' labs suggests that there is a theoretical limit in what you can do with any one approach to teleoperation so reaching beyond this limit requires a careful integration of multiple technologies (Atherton & Goodrich, 2013). For example, there are theoretical limits in terms of both the time to create robot behaviors via off-line teleoperation and the expressivity of these behaviors. These limitations in developing robot autonomy in turn require that operators have greater understanding and control of the robot's (potentially faulty) autonomy during run-time (Harutyunyan, et al., 2012). Thus, a key research question is how to best combine different ways of creating and managing algorithms and displays for teleoperating a humanoid robot.

Another manifestation of the need to integrate is the presence of multiple channels of interaction between the operator and the humanoid. For example, the humanoid may track the operator with a camera allowing the operator to control behavior via gesture, and the humanoid and the operator may engage in verbal dialog. Although such natural interactions are nice, they may not be the only types of interactions allowed and, importantly, will only occur if the operator and the humanoid are near each other. Other interactions, such as those discussed in the first paragraph, will occur through some sort of mediating interface.

A final manifestation of the need to integrate is the presence of multiple robot functions that must be coordinated. As a concrete example, consider a situation where the humanoid can walk, can manipulate objects, and has the capacity for engaging in dialog. Each of these aspects may include input from the robot's operator, but the social-emotional and physical response of an interactant is likely to be a function of the coordination of each element. If, for example, a robot is engaged in small-talk with an interactant while violating rules of physical praxemics and reaching out a hand to manipulate an object, the response of the interactant may be very negative. Integrating the robot's speech with its physical behaviors is likely to be important since the gestalt perception of the robot by an interactant is likely to be more than the sum of its parts.

B. Research Challenges

Having summarized some some common solution themes, it is useful to review some of the open challenges in teleoperation of humanoids. We discuss three: (1) reducing the cost of humanoid robots, (2) determining who operators the robot, and (3) using models of human-robot interaction to enhance teleoperation.

1. The Cost of Humanoid Robots

Although not mentioned in the body of the paper, from both the operator/problem-holder and the stakeholder/client perspective, cost matters (Chadwick, Gillan, Simon, & Pazuchanics, 2004). The widespread adoption of household robots such as robot vacuum cleaners (Forlizzi & DiSalvo, 2006; Sung et al., 2009) is possible because these robots are relatively cheap. Many current humanoid robots, by contrast, are relatively expensive (e.g., the Robonaut, the PR2 from Willow Garage, and the iCub). Affordable, commercial-grade humanoid robots are required for wide-scale adoption (E. I. Barakova & Lourens, 2010; Manohar, Marzooqi, & Crandall, 2011; Wikipedia, 2012d), especially for many envisioned applications such as eldercare.

2. Who Operates the Robot?

An important, but complex, open question is: *"who" operates a teleoperated humanoid*? It is often unrealistic and perhaps even undesirable to assume that a single human is operating the humanoid. As Murphy has often pointed out in the context of fielded deployments of air and ground robots, operation often involves or requires many humans (Casper & Murphy, 2003; Murphy, Griffin, Stover, & Pratt, 2006; R. Murphy, Stover, Pratt, & Griffin, 2006). This is apparent in traditional teleoperation when multiple humans must coordinate to control several degrees of freedom, either in real-time or across planning periods. It is also apparent when one person programs an autonomous response and another uses this response as part of his or her method of teleoperation via plays or scripts. Multiple operator control is also apparent in more complex situations such as those that arise in assistive contexts when many members of a team must coordinate activities to successfully use a robot in real therapies (Barakova et al., 2012a; Goodrich et al., 2012; Kim et al., 2012). Teleoperation interfaces must be designed to support the workflow of real teams (Michaud et al., 2010), which may mean that multiple humans share authority to task and shape humanoid behaviors. For this purpose, mixed reality interfaces (Dragone et al., 2007), networked immersive user interfaces (Sandygulova et al., 2012), tangibles (Randelli, Venanzi, & Nardi, 2011), and Wii consoles have been used.

At the other end of the question of who operates a humanoid is the observation that there is an inflationary pressure toward having a human teleoperate or manage many robots. Advances in autonomy motivate the natural need to leverage human expertise across a wider scale, as illustrated in Figure 3.

This pressure is seen in other robot applications and is likely to emerge in the teleoperation of humanoids (Cummings, Nehme, Crandall, & Mitchell, 2007; Whetten, Goodrich, & Guo, 2010; Cummings, Bruni, Mercier, & Mitchell, 2007; Goodrich, 2010; Squire, Trafton, & Parasuraman, 2006). This pressure is naturally derived from the desire to maximize human usefulness and is finding its way into the teleoperation of humanoids (Glas et al., 2008). Lessons from other areas of robotics suggest that many behaviors can be automated enough to allow the basic teleoperation of multiple robots, but that problem holder-level strategies and sensor management require sufficient human attention to allow the robot handler to make strategic decisions within some broad mission context.

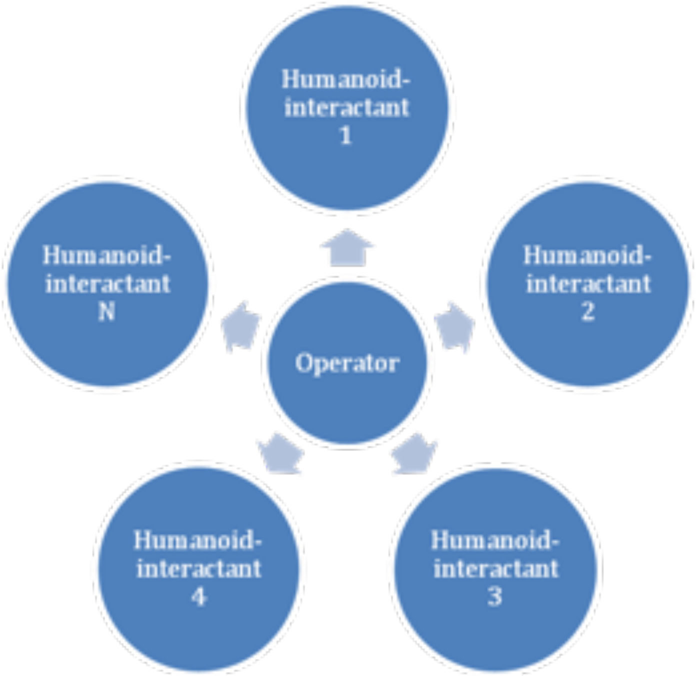

Figure 3. Scaling teleoperation to multiple humanoids in multiple social contexts (or a mixed culture of humanoids and interactants).

In between having multiple operators and having an overworked single operator is a tendency for some operators to desire complete control (Kron et al., 2004) rather than to treat robots as collaborative teammates (Breazeal, Hoffman, & Lockerd, 2004). On one hand, a sense of remote presence and absolute control may be *desirable for high stakes* situations such as disposal of improvised explosive devices and surgery, but absolute presence and control may be *undesirable in highly paced* situations or when social presence is more important than precise motions. It is likely that this tension between control and collaboration will be amplified for humanoids, partly because of their high degrees of freedom and partly because of their potential for being used in socially relevant problems that have high pace and great complexity, and that occur in unstructured environments.

3. Using Models

Because of the complexity of managing integrated autonomy while supporting the dual ecology, there is another fundamental factor that must be addressed in the teleoperation of humanoid robots, namely the need to understand and model various parts of the interaction, including social interaction. As robot capabilities and appearance evolve, social expectations will also evolve yielding a moving target for the development of teleoperation for humanoid robots. This may include advances in understanding, modeling, and replicating developments in neurosciences using AI, machine learning, and control that scale to the narrative-basis for interesting and useful teleoperation. Part of this modeling includes the need to understand the fundamental limits of human skill, dexterity, and perception thereby facilitating the ability to appropriately assemble behavioral, social and communication units.

Importantly, modeling may become essential as humanoid robots gain greater similarity with humans (e.g., the soft robots of Pfeifer, Ishiguro's life-like robots, and the Maskbot of Cheng [Kuratate, Matsusaka, Pierce, & Cheng, 2011]). For example, morphological similarities between human and robot may make online teleoperation easier through the use of exoskeleton or control via inertial sensors, but increase the difficulty of properly modeling and engaging in social interaction (Mori, 1970).

In addressing the question of who will operate the robot, it is likely that new "Ironies of Automation" (Bainbridge, 1983) will emerge as humanoid robots mature and are introduced more deeply into daily life. Potential examples for humanoids include issues associated with the "Uncanny Valley" (MacDorman & Ishiguro, 2006; Mori, 1970), user interface issues such as the "Naïve Realism" trap that suggests that deeper and deeper realism is an advantage to operators (Smallman & John, 2005), and the magnitude of hidden costs associated with operator training and robot maintenance. Additionally, to help support this type of human-multiple humanoid interaction, there is a need to model essential aspects of the dual ecology problem, thereby making it possible to analyze tradeoffs and finding balance. While it is certainly possible to make advances in these areas by iteratively designing robots and interactions, models of human perception and interaction may be necessary to allow rapid progress in avoiding these ironies.

Finally, modeling the fundamental technological limitations that must be managed may help facilitate advances in teleoperation. Models can potentially be used to help manage bandwidth by facilitating, for example, abstracting and organizing communications into representations and packages that facilitate interaction. These models can include variations in communication including communication channel limits or the operational tempo of the interaction, both of which may make it impossible to manage all degrees of robot freedom in a proximate interaction.

References

Adalgeirsson, S. O., & Breazeal, C. (2010). Proceedings from the 5th ACM/IEEE International Conference on Human-Robot Interaction: *MeBot: A robotic platform for socially embodied presence*. Osaka, Japan.

Akgun, B., Cakmak, M., Yoo, J., & Thomaz, A. L. (2012). Proceedings from the International Conference on Human-Robot Interaction (HRI): *Trajectories and keyframes for kinesthetic teaching: A human-robot interaction perspective*. Boston, Massachusetts, USA.

Ambrose, R. O., Aldridge, H., Askew, R. S., Burridge, R. R., Bluethmann, W., Diftler, M., . . . Rehnmark, F. (2000). Robonaut: NASA's space humanoid. *IEEE Intelligent Systems and Their Applications, 15*(4), 57-63.

Andrade, K. O., Ito, G. G., Joaquim, R. C., Jardim, B., Siqueira, A. A. G., Caurin, G. A. P., & Becker, M. (2010). Proceedings from the Brazilian Symposium on Games and Digital Entertainment (SBGAMES): *A robotic system for rehabilitation of distal radius fracture using games.* Florianópolis–SC, Brazil

Anusuya, M. A., & Katti, S. K. (2009). Speech recognition by machine, a review. *International Journal of Computer Science and Information Security, 6*(3), 181-205.

Argall, B., Browning, B., & Veloso, M. (2007). Proceedings from the 2nd Annual Conference on Human-Robot Interactions: *Learning by demonstration with critique from a human teacher*. Washington DC, USA.

Argall, B. D., Chernova, S., Veloso, M., & Browning, B. (2009). A survey of robot learning from demonstration. *Robotics and Automation, 57*(5), 269-483.

Arkin, R. C. (2008). Proceedings from the 3rd ACM/IEEE International Conference on Human Robot Interaction: *Governing lethal behavior: Embedding ethics in a hybrid deliberative/reactive robot architecture*. Amsterdam, The Netherlands.

Atherton, J. A., & Goodrich, M. A. (2013). Proceedings from the 8th ACM/IEEE RAS International Conference on Human-Robot Interaction: *Enabling clinicians to rapidly animate robots*. Tokyo, Japan.

Bainbridge, L. (1983). Ironies of automation. *Automatica, 19*(6), 775-779.

Balakrishna, D., Sailaja, P., Rao, R. V. V. P., & Indurkhya, B. (2010). Proceedings from the IEEE International Conference on Robotics and Biomimetics (ROBIO): *A novel human robot interaction using the Wiimote.* Tianjin, China.

Barakova, E., & Feijs, L. (2011). Brain-inspired robots for autistic training and care. In J. L. Krichmar & H. Wagatsuma (Eds.), *Neuromorphic and Brain-Based Robots: Trends and Perspectives* (pp. 178-214). New York: Cambridge University Press.

Barakova, E., & Lourens, T. (2010). Expressing and interpreting emotional movements in social games with robots. *Personal and Ubiquitous Computing, 14*(5), 457-467. doi:10.1007/s00779-009-0263-2

Barakova, E. I. (2011). Proceedings from the IEEE WICT: *Empowering the therapists in intensive training programs*. Mumbai, India.

Barakova, E. I., & Chonnaparamutt, W. (2009). Timing sensory integration: Robot simulation of autistic behavior. *IEEE Robotics and Automation Magazine, 16*(3), 51-58.

Barakova, E. I., Gillesen, J. C. C., Huskens, B. E. B. M., & Lourens, T. (2012). End-user programming architecture facilitates the uptake of robots in social therapies. *Robotics and Autonomous Systems*. Available online 20 August 2012, 10.1016/j.robot.2012.08.001.

Bartneck, C., Namura, T., Kanda, T., Suzuki, T., & Kato, K. (2005). Proceedings from the HCI International Conference: *A cross-cultural study on attitudes towards robots*. Las Vegas, Nevada, USA.

Beasley, R. A. (2012). Medical robots: Current systems and research directions. *Journal of Robotics*, vol 2012 (2012). Article ID 401613, 14 pages. doi:10.1155/2012/401613

Bera, D., van Hee, K. M., & van der Werf, J. M. (2012). Proceedings from the 33rd International Conference on Application and Theory of Petri nets: *Designing weakly terminating ROS systems*.

Bergamasco, M., Allotta, B., Bosio, L., Ferretti, L., Parrini, G., Prisco, G. M., . . . Sartini, G. (1994). Proceedings from the IEEE International Conference on Robotics and Automation: *An arm exoskeleton system for teleoperation and virtual environments applications.* San Diego, California, USA.

Bermudez, F. L. G., Julian, R. C., Haldane, D. W., Abbeel, P., & Fearing, R. S. (2012). Proceedings from the IEEE-INNS-ENNS International Joint Conference on Neural Networks: *Performance analysis and terrain classification for a legged robot over rough terrain*. Lausanne, Switzerland.

Billard, A., Robins, B., Nadel, J., & Dautenhahn, K. (2007). Building Robota, a mini-humanoid robot for the rehabilitation of children with autism. *RESNA Assistive Technology Journal,* 19(1), 37-49.

Bolopion, A., Millet, G., Pacoret, C., & Regnier, S. (2013). Haptic feedback teleoperation for the micro and nano worlds. In D. Kaber (Ed.), *Reviews in Human Factors and Ergonomics*, under review.

Borst, C., Wimböck, T., Schmidt, F.; Fuchs, M., Brunner, B., Zacharias, F., … Hirzinger, G. (2009). Proceedings of the IEEE International Conference on Robotics and Automation (ICRA): *Rollin' Justin – Mobile platform with variable base*. Kobe, Japan.

Boston Dynamics. (2012). DARPA Cheetah Sets Speed Record for Legged Robots. Retrieved from http://www.youtube.com/watch?v=d2D71CveQwo.

Bradshaw, J. M., Acquisti, A., Allen, J., Breedy, M., Bunch, L., Chambers, N., . . . van Hoof, R. (2004). Proceedings from the AAAI Spring Symposium on Interaction Between Humans and Autonomous Systems Over Extended Operation: *Teamwork-centered autonomy for extended human-agent interaction in space applications*. Stanford, CA.

Bradshaw, J. M., Feltovich, P. J., Jung, H. , Kulkarni, S., Taysom, W, & Uszok, A. (2004). Dimensions of adjustable autonomy and mixed-initiative interaction. In M. Nickles, Rovatos, M., and Weiss, G. (Eds.), *Agents and computational Autonomy: Potential, Risks, and Solutions* (Vol. 2969, pp. 17-39). Berlin/Heidelberg, Germany: Springer.

Breazeal, Cynthia. (2012). MeBot. MIT Media Lab. Retrieved from: http://robotic.media.mit.edu/projects/robots/mebot/overview/overview.html

Breazeal, C., Hoffman, G., & Lockerd, A. (2004). Proceedings from the 3rd International Joint Conference on Autonomous Agents and Multiagent Systems (AAMAS): *Teaching and working with robots as a collaboration*. New York, USA.

Brick, T., & Scheutz, M. (2007). Proceedings from the ACM/IEEE International Conference on Human-Robot Interaction: *Incremental natural language processing for HRI*. Arlington, VA.

Brok, J. and E. Barakova (2010). Engaging autistic children in imitation and turn-taking games with multiagent system of interactive lighting blocks. In H. Yang, R. Malaka, J. Hoshino & J. Hans (Eds), *Entertainment Computing - ICEC 2010*, 6243: 115-126: Springer Berlin / Heidelberg.

Brokaw, E. B., Murray, T. M., Nef, T., Lum, P. S., Brokaw, E. B., Nichols, D., & Holley, R. J. (2011). Proceedings from the IEEE International Conference on Rehabilitation Robotics (ICORR): *Time independent functional task training: A case study on the effect of inter-joint coordination driven haptic guidance in stroke therapy.* Zurich, Switzerland.

Bruemmer, D. J., Nielsen, C. W., & Gertman, D. I. (2008). Proceedings from the 3rd ACM/IEEE International Conference on Human Robot Interaction: *How training and experience affect the benefits of autonomy in a dirty-bomb experiment*. Amsterdam, The Netherlands.

Burgard, W., Cremers, A. B., Fox, D., Hähnel, D., Lakemeyer, G., Schulz, D., . . . Thrun, S. (1999). Experiences with an interactive museum tour-guide robot. *Artificial Intelligence*. 114(1): 3-55.

Burnett, M. M. (1999). Visual Programming. In J. G. Webster (Ed.), *Encyclopedia of Electrical and Electronics Engineering*. John Wiley & Sons Inc, Hoboken, New Jersey, USA.

Calinon, S., & Billard, A. (2009). Statistical learning by imitation of competing constraints in joint space and task space. *Advanced Robotics, 23*(15), 2059-2076.

Calinon, S., Guenter, F., & Billard, A. (2007). On learning, representing and generalizing a task in a humanoid robot. *IEEE Transactions on Systems, Man and Cybernetics, Part B, 37*(2), 286-298.

Casper, J., & Murphy, R. R. (2003). Human-robot interactions during the robot-assisted urban search and rescue response at the World Trade Center. *IEEE Transactions on Systems, Man and Cybernetics, Part B, 33*(3), 367-385.

Chadwick, R. A., Gillan, D. J., Simon, D., & Pazuchanics, S. (2004). Proceedings from the Human Factors and Ergonomics Society Annual Meeting: *Cognitive analysis methods for control of multiple robots: Robotics on $5 a day*. New Orleans, Lousiana, USA.

Chambers, A. B., & Nagel, D. C. (1985). Pilots of the future: Human or computer? *Communications of the ACM, 28*(11), 1187-1199. doi:10.1145/4547.4551

Chaminade, T., & Cheng, G. (2009). Social cognitive neuroscience and humanoid robotics. *Journal of Physiology-Paris, 103*(3–5), 286-295. doi:10.1016/j.jphysparis.2009.08.011

Chen, J. Y. C., & Barnes, M. J. (2008). Proceedings from the 3rd ACM/IEEE International Conference on Human Robot Interaction: *Robotics operator performance in a military multi-tasking environment*. Amsterdam, The Netherlands.

Chen, T. L., & Kemp, C. C. (2011). A direct physical interface for navigation and positioning of a robotic nursing assistant. *Advanced Robotics, 25*, pp 605-627.

Chernova, S., & Veloso, M. (2008). Proceedings from the 3rd ACM/IEEE International Conference on Human-Robot Interaction: *Multi-thresholded approach to demonstration selection for interactive robot learning.* Amsterdam, The Netherlands.

Chestnutt, J., Lau, M., Cheung, G., Kuffner, J., Hodgins, J., & Kanade, T. (2005). Proceedings from the IEEE International Conference on Robotics and Automation (ICRA): *Footstep planning for the Honda ASIMO humanoid.* Barcelona, Spain.

Cobo, L. C., Isbell, C. L., & Thomaz, A. L. (2012). Proceedings from the 9th International Conference on Autonomous Agents and Multiagent Systems (AAMAS): *Automatic task decomposition and state abstraction from demonstration*. Valenca, Sain

Congcong, L., Wong, T. P., Xu, N., & Saxena, A. (2011). Proceedings from the IEEE International Conference on Robotics and Automation (ICRA): *FeCCM for scene understanding: Helping the robot to learn multiple tasks.* Shanghai, China.

Corradini, A. (2000). Proceedings from the IEEE-INNS-ENNS International Joint Conference on Neural Networks: *Camera-based gesture recognition for robot control*. Como, Italy.

Crandall, J. W., & Goodrich, M. A. (2002a). Proceedings from the AAAI Fall Symposium Human-Robot Interaction Workshop: *Principles of adjustable interactions*. North Falmouth, MA.

Crandall, J. W., & Goodrich, M. A. (2002b). Proceedings from the IEEE/RSJ International Conference on Intelligent Robots and Systems: *Characterizing efficiency of human-robot interaction: A case study of shared-control teleoperation*. Lausanne, Switzerland.

Crandall, J. W., & Cummings, M. L. (2007). Identifying predictive metrics for supervisory control of multiple robots. *IEEE Transactions on Robotics, 23*(5), 942-951.

Crandall, J. W., Goodrich, M. A., Olsen Jr., D. R. , & Nielsen C. W. (2005). Validating human-robot interaction schemes in multi-tasking environments. *IEEE Transactions on Systems, Man, and Cybernetics: Part A—Systems and Humans, 35*(4), 438-449.

Cummings, D., Fymat, S., & Hammond, T. (2012). Proceedings from the 2012 ACM Annual Conference Extended Abstracts on Human Factors in Computing Systems: *Sketch-based interface for interaction with unmanned air vehicles*. Austin, Texas.

Dariush, B., Gienger, M., Jian, B., Goerick, C. & Fujimura, K. (2008). Proceedings from the IEEE International Conference on Robotics and Automation (ICRA): *Whole body humanoid control from human motion descriptors*. Pasadena, CA.

Dautenhahn, K. (2007). Socially intelligent robots: Dimensions of human–robot interaction. *Philosophical Transactions of the Royal Society B: Biological Sciences, 362*(1480), 679-704.

Dautenhahn, K., Walters, M., Woods, S., Koay, K. L., Nehaniv, C. L., Sisbot, A., . . . Simeon, T. (2006). Proceedings from the 1st ACM SIGCHI/SIGART Conference on Human-Robot Interaction: *How may I serve you? A robot companion approaching a seated person in a helping context*. Salt Lake City, UT.

Diehl, J. J., L. M. Schmitt, et al. (2012). The clinical use of robots for individuals with autism spectrum disorders: A critical review." *Research in Autism Spectrum Disorders*, *6*(1): 249-262.

DiSalvo, C. F., Gemperle, F., Forlizzi, J., & Kiesler, S. (2002). Proceedings from the 4th Conference on Designing Interactive Systems: Processes, Practices, Methods, and Techniques: *All robots are not created equal: The design and perception of humanoid robot heads*. London, England.

Dragone, M., Holz, T., & O'Hare, G. M. P. (2007). Proceedings from the the 16th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN): *Using mixed reality agents as social interfaces for robots*. (pp. 1161-1166). doi:10.1109/roman.2007.4415255

Drucker, P. F. (1954). *The Practice of Management*: Harper Collins, New York, USA.

Duquette, A., Michaud, F., & Mercier, H. (2008). Exploring the use of a mobile robot as an imitation agent with children with low-functioning autism. *Autonomous Robots, 24*(2), 147-157. doi:10.1007/s10514-007-9056-5

Edsinger, A. (2007). Proceedings from the International Conference on Advanced Robotics (ICRA): *Two arms are better than one: A behavior-based control system for assistive bimanual manipulation*. Roma, Italy

Endsley, M., Bolte, B., & Jones, D. (2003). *Designing for situation awareness: An approach to user-centered design*. New York: Taylor and Francis.

Eriksson, J., Mataric, M. J., & Winstein, C. J. (2005). Proceedings from the 9th International Conference on Rehabilitation Robotics (ICORR): *Hands-off assistive robotics for post-stroke arm rehabilitation.* Chicago, Illinois, USA.

Delbressine, F., Beursgens, L., de Jong, M., van Dam, A., Verweij, D., Janssen, M., & Markopoulos, P. (2012). Proceedings from the 34th Annual International Conference of the IEEE Engineering in Medicine and Biology Society: *Motivating arm-hand use for stroke patients by serious games.* San Diego, CA.

Fails, J. A., & Olsen Jr., D. R. (2003). Proceedings from the 8th International Conference on Intelligent User Interfaces: *Interactive machine learning*. Miami, Florida, USA.

Fan, A., King, C.-H., Darb, H., & Kemp, C. C. (2010). Proceedings from the International Symposium on Quality of Life Technology: *Dusty: A teleoperated assistive mobile manipulator that retrieves objects from the floor.* Las Vegas, Nevada, USA.

Fasola, J., & Mataric, M. J. (2012). Using socially assistive human-robot interaction to motivate physical exercise for older adults. *Proceedings of the IEEE, 100*(8), 2512-2526. doi:10.1109/jproc.2012.2200539

Feil-Seifer, D., & Mataric, M. J. (2005). Proceedings from the 9th IEEE International Conference on Rehabilitation Robotics (ICORR): *Defining socially assistive robotics.* Chicago, Illinois, USA.

Feil-Seifer, D. J., & Mataric, M. J. (2008). Proceedings from the 7th International Conference on Interaction Design for Children: Children with Special Needs: *Robot-assisted therapy for children with autism spectrum disorders*. Chicago, Illinois, USA.

Ferketic, J., Goldblatt, L., Hodgson, E., Murray, S., Wichowski, R… Erkorkmaz, C. (2006). Proceedings from AIAA Space: *Toward human-robot interface standards II: A closer examination of common elements in human-robot interactions across the space enterprise*. AIAA-2006-7388. San Jose, California, USA.

Ferland, F., Létourneau, D., Aumont, A., Frémy, J., Legault, M. A., Lauria, M., & Michaud, F. (2012). Natural interaction design of a humanoid robot. *Journal of Human-Robot Interaction*, *1*(2), 118-134.

Fong, T., & Thorpe, C. (2001). Vehicle teleoperation interfaces. *Autonomous Robots, 11*(1), 9-18.

Fong, T., Scholtz, J., Shah, J. A., Fluckiger, L., Kunz, C., Lees, D., . . . Trafton, J. G. (2006). Proceedings from the IEEE International Conference on Systems, Man and Cybernetics (SMC '06): *A preliminary study of peer-to-peer human-robot interaction.* Taipei, Taiwan.

Fong, T., Thorpe, C., & Baur, C. (2001). Proceedings from the IEEE International Conference on Advanced Robotics (ICRA): *A safeguarded teleoperation controller*. Seoul, Korea.

Fong, T., Thorpe, C., & Baur, C. (2003). Proceedings from the 10th International Symposium of Robotics Research: *Collaboration, dialogue, and human-robot interaction*. Berlin, Germany: Springer.

Forlizzi, J., & DiSalvo, C. (2006). Proceedings from the First ACM International Conference on Human Robot Interaction: *Service robots in the domestic environment: A study of the Roomba Vacuum in the home*, Salt Lake City, UT.

Fréchette, M., Létourneau, D., Valin, J-M., & Michaud, F. (2012). Proceedings of the IEEE/RSJ International Conference on Robots and Systems (IROS): *Integration of sound source localization and separation to improve dialogue management on a robot*, Vilamoura, Algarve Portugal.

Gillesen, J. C. C., Barakova, E. I., Huskens, B. E. B. M., & Feijs, L. M. G. (2011). Proceedings from the IEEE International Conference on Rehabilitation Robotics (ICORR): *From training to robot behavior: Towards custom scenarios for robotics in training programs for ASD.* Zurich, Switzerland.

Giullian, N., Ricks, D., Atherton, A., Colton, M., Goodrich, M. A., & Brinton, B. (2010). Proceedings from the IEEE International Conference on Systems, Man and Cybernetics: *Detailed requirements for robots in autism therapy.* Istanbul, Turkey.

Glas, D. F., Kanda, T., Ishiguro, H., & Hagita, N. (2008). Proceedings from the 3rd ACM/IEEE International Conference on Human Robot Interaction: *Simultaneous teleoperation of multiple social robots*. Amsterdam, The Netherlands.

Glas, D. F., Kanda, T., Ishiguro, H., & Hagita, N. (2012). Teleoperation of multiple social robots. *IEEE Transactions on Systems Man and Cybernetics Part A—Systems and Humans, 42*(3), 530-544. doi: 10.1109/tsmca.2011.2164243

Gockley, R., Bruce, A., Forlizzi, J., Michalowski, M., Mundell, A., Rosenthal, S., . . . Jue, W. (2005). Proceedings from the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS): *Designing robots for long-term social interaction.* Edmonton, Alberta, Canada.

Goodrich, M. A. (2010). On maximizing fan-out: Towards controlling multiple unmanned vehicles. In M. Barnes & F. Jentsch (Eds.), *Human-Robot Interactions in Future Military Operations*. Surrey, England: Ashgate Publishing.

Goodrich, M. A., & Schultz, A. C. (2007). Human-robot interaction: A survey. *Foundations and Trends in Human-Computer Interaction, 1*(3), 203-275.

Goodrich, M. A., Colton, M., Brinton, B., Fujiki, M., Atherton, J. A., Robinson, L., . . . Acerson, A. (2012). Incorporating a robot into an autism therapy team. *IEEE Intelligent Systems*, 27(2), 52-59.

Goodrich, M. A., & Mercer, E. G. (2012). Proceedings from Infotech@Aerospace: *Abstraction and persistence: Macro-level guarantees of collective bio-inspired teams under human supervision*. Garden Grove, CA.

Goodrich, M. A., & Olsen, D. R. (2003). Proceedings from the IEEE International Conference on Systems, Man and Cybernetics: *Seven principles of efficient interaction*. Washington DC, USA.

Goodrich, M. A., Sujit, P. B., Pendleton, B., & Pinto, J. (2011). Proceedings from the IEEE International Conference on Systems, Man, and Cybernetics: *Toward human interaction with bio-inspired robot teams*.Anchorage, Alaska, UAS.

Goza, S. M., Ambrose, R. O., Diftler, M. A., & Spain, I. M. (2004). Proceedings from the ACM SIGCHI Conference on Human Factors in Computing Systems: *Telepresence control of the NASA/DARPA robonaut on a mobility platform*. Vienna, Austria.

Gray, S., Clingerman, C., Likhachev, M., & Chitta, S. (2011). Proceedings from the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) PR2 Workshop: *PR2: Opening spring-loaded doors*. San Francisco, California, USA.

Green, A., Huttenrauch, H., & Eklundh, K.S. (2004). Proceedings from the IEEE International Workshop on Robot and Human Interactive Communication (RO-MAN): *Applying the Wizard-of-Oz framework to cooperative service discovery and configuration*. Kurashiki, Japan.

Groom, V., Takayama, L., Ochi, P., & Nass, C. (2009). Proceedings from the 4th ACM/IEEE International Conference on Human Robot Interaction: *I am my robot: The impact of robot-building and robot form on operators*. La Jolla, CA.

Guo, S., Zhang, H., & Hata, S. (2002). Proceedings from the 4th World Congress on Intelligent Control and Automation. *Complex control of a human scale tele-operating system for cell biology*. Shanghai, China.

Haans, A., & IJsselsteijn, W. A. (2012). Embodiment and telepresence: Toward a comprehensive theoretical framework. *Interacting with Computers, 24*(4) 211-218. doi: 10.1016/j.intcom.2012.04.010

Ham, R., Sugar, T., Vanderborght, B., Hollander, K., & Lefeber, D. (2009). Compliant actuator designs. *Robotics & Automation Magazine, IEEE, 16*(3), 81-94. doi:10.1109/mra.2009.933629

Harada, K., Hasunuma, H., Nakashima, K., Kawai, Y., & Hirukawa, H. (2008). Task autonomy for a teleoperated humanoid robot. In O. Khatib, V. Kumar & D. Rus (Eds.), *Experimental Robotics, 39,* 533-540. Berlin/Heidelberg, Germany: Springer.

Hardin, B., & Goodrich, M. A. (2009). Proceedings from the ACM/IEEE International Conference on Human-Robot Interaction: *On using mixed-initiative control: A perspective for managing large-scale robotic teams*. San Diego, California, USA.

Harutyunyan, V., Manohar, V., Gezehei, I., & Crandall, J. W. (2012). Cognitive telepresence in human-robot interactions. *The Journal of Human-Robot Interaction*, 1(2), 158-182. doi: 10.5898/JHRI.1.2.Harutyunyan

Hodges, K. & Schmitt, H. (2010). A new paradigm for advanced planetary analog exploration exercises on Earth. *Geologic Society of America Special Paper*, 483, 17-31. doi:10.1130/2011.2483(02)

Honda. (2012). Honda latest ASIMO robot running—Best humanoid robots! Retrieved from http://www.youtube.com/watch?v=nFSXJ2JPX9o.

Hornstein, J., Lopes, M., Santos-Victor, J., & Lacerda, F. (2006). Proceedings from the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS): *Sound localization for humanoid robots—Building audio-motor maps based on the HRTF*. Beijing, China.

Hornyak, T. (2006). Android science. *Scientific American* 294, 32-34. doi:10.1038/scientificamerican0506-32

Huettenrauch, H., Eklundh, K. S., Green, A., & Topp, E. A. (2006). Proceedings from the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS): *Investigating spatial relationships in human-robot interaction.* Beijing, China.

Huskens, B., Verschuur, R., Gillesen, J., Didden, R., & Barakova, E. *(2013*). Promoting question-asking in school-aged children with autism spectrum disorders: Effectiveness of a robot intervention compared to a human-trainer intervention. *Developmental Neurorehabilitation,* 1-12. doi: 10.3109/17518423.2012.739212

Ishiguro, H. (2006). Android science: conscious and subconscious recognition. *Connection Science, 18*(4), 319-332.

Jain, A., Killpack, M. D., Edsinger, A., & Kemp, C. C. (2012). *Manipulation in clutter with whole-arm tactile sensing*. Paper under review. Retrieved from http://www.hsi.gatech.edu/hrl/pdf/haptic_manipulation_clutter.pdf.

Kaber, D. B., & Endsley, M. R. (2004). The effects of level of automation and adaptive automation on human performance, situation awareness and workload in a dynamic control task. *Theoretical Issues in Ergonomics Science, 5*(2), 113-153.

Kamide, H., Mae, Y., Kawabe, K., Shigemi, S., Hirose, M., & Arai, T. (2012). Proceedings from the 7th ACM/IEEE International Conference on Human-Robot Interaction: *New measurement of psychological safety for humanoid*. Boston, MA.

Kanda, T., Hirano, T., Eaton, D., & Ishiguro, H. (2004). Interactive robots as social partners and peer tutors for children: A field trial. *Human-Computer Interaction, 19*(1-2), 61-84.

Kanda, T., Shiomi, M., Miyashita, Z., Ishiguro, H., & Hagita, N. (2010). A communication robot in a shopping mall. *IEEE Transactions on Robotics, 26*(5), 897-913. doi:10.1109/tro.2010.2062550

Kang, H., Hebert, M., & Kanade, T. (2011). Proceedings from the IEEE International Conference on Computer Vision: *Discovering object instances from scenes of daily living*. Barcelona, Spain.

Kaplan, F. (2004). Who is afraid of the humanoid? Investigating cultural differences in the acceptance of robots. *International Journal of Humanoid Robotics, 1*(3), 1-16.

Kelley, J. F. (1984). An iterative design methodology for user-friendly natural language office information applications. *ACM Transactions on Information Systems, 2*(1), 26-41. doi:10.1145/357417.357420

Kennedy, B., Agazarian, H., Cheng, Y., Garrett, M., Hickey, G., Huntsberger, T., . . . Knight, J. (2001). LEMUR: Legged Excursion Mechanical Utility Rover. *Autonomous Robots, 11*(3), 201-205. doi: 10.1023/a:1012474603861

Kennedy, W. G., Bugajska, M. D., Marge, M., Adams, W., Fransen, B. R., Perzanowski, D., . . . Trafton, J. G. (2007). Proceedings from the 22nd National Conference on Artificial Intelligence: *Spatial representation and reasoning for human-robot collaboration*. Vancouver, British Columbia, Canada.

Keyrouz, F., & Diepold, K. (2007). Binaural source localization and spatial audio reproduction for telepresence applications. *Presence, 16*(5), 509-522. doi:10.1162/pres.16.5.509

Kim, E. S., Paul, R., Shic, F., & Scassellati, B. (2012). Bridging the research gap: Making HRI useful to individuals with autism. *Journal of Human-Robot Interaction, 1*(1), 26-54.

Knox, W. B., & Stone, P. (2010). Proceedings from the 9th International Conference on Autonomous Agents and Multiagent Systems (AAMAS): *Combining manual feedback with subsequent MDP reward signals for reinforcement learning*. Toronto, Canada.

Koyama, T., Yamano, I., Takemura, K., & Maeno, T. (2002). Proceedings from the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS): *Multi-fingered exoskeleton haptic device using passive force feedback for dexterous teleoperation.* Lausanne, Switzerland.

Kozima, H., Nakagawa, C., & Yasuda, Y. (2005a). Proceedings from the IEEE International Workshop on Robot and Human Interactive Communication (RO-MAN): *Interactive robots for communication-care: a case-study in autism therapy.* Nashville, Tennessee, USA.

Kozima, H., Nakagawa, C., & Yasuda, Y. (2005b). Proceedings from the IEEE International Symposium on Computational Intelligence in Robotics and Automation: *Designing and observing human-robot interactions for the study of social development and its disorders*. Espoo, Finland.

Krebs, H., Dipietro, L., Levy-Tzedek, S., Fasoli, S., Rykman-Berland, A., Zipse, J., . . . Hogan, N. (2008). A paradigm shift for rehabilitation robotics. *Engineering in Medicine and Biology Magazine, IEEE, 27*(4), 61-70. doi:10.1109/memb.2008.919498

Krebs, H. I., Hogan, N., Aisen, M. L., & Volpe, B. T. (1998). Robot-aided neurorehabilitation. *IEEE Transactions on Rehabilitation Engineering, 6*(1), 75-87. doi:10.1109/86.662623

Kron, A., Schmidt, G., Petzold, B., Zah, M. I., Hinterseer, P., & Steinbach, E. (2004). Proceedings from the IEEE International Conference on Robotics and Automation (ICRA): *Disposal of explosive ordnances by use of a bimanual haptic telepresence system*. Barcelona, Spain.

Kuratate, T., Matsusaka, Y., Pierce, B., & Cheng, G. (2011). Proceedings from the 11th IEEE-RAS International Conference on Humanoid Robots (Humanoids): *Mask-bot: A life-size robot head using talking head animation for human-robot communication.* Bled, Slovenia.

Kuzuoka, H., Yamazaki, K., Yamazaki, A., Kosaka, J. i., Suga, Y., & Heath, C. (2004). Proceedings from the ACM Conference on Human Factors in Computing Systems (SIGCHI): *Dual ecologies of robot as communication media: thoughts on coordinating orientations and projectability*. Vienna, Austria.

Labonte, D., Boissy, P., & Michaud, F. Comparative analysis of 3-D robot teleoperation interfaces with novice users (2010). *IEEE Transactions on Systems, Man, and Cybernetics, Part B: Cybernetics*. 40(5), 1331-1342.

Leary, M. R., & Hill, D. A. (1996). Moving on: Autism and movement disturbance. *Mental Retardation, 34*(1), 39-53.

Letier, P., Motard, E., & Verschueren, J.-P. (2010). Proceedings from the IEEE International Conference on Robotics and Automation (ICRA): *EXOSTATION: Haptic exoskeleton based control station*. Anchorage, Alaska, USA.

Li, L., Socher, R., & Fei-Fei, L. (2009). Proceedings from the IEEE Computer Society Conference on Computer Vision and Pattern Recognition: *Towards total scene understanding: Classification, annotation and segmentation in an automatic framework.*

Lord, C. & Bishop, S. L. (2009). The autism spectrum: definitions, assessment and diagnoses. *British Journal of Hospital Medicine*, 70(3): 132-135.

Lourens, T., van Berkel, R., & Barakova, E. (2010). Communicating emotions and mental states to robots in a real time parallel framework using Laban movement analysis. *Robotics and Autonomous Systems, 58*(12), 1256-1265. doi:10.1016/j.robot.2010.08.006

Lu, Y., Huang, Q., Li, M., Jiang, X., & Keerio, M. (2008). Proceedings from the 7th World Congress on Intelligent Control and Automation: *A friendly and human-based teleoperation system for humanoid robot using joystick*. Chongqing, China.

Lu, Y., Liu, L., Chen, S., & Huang, Q. (2010). Proceedings from the International Conference on Intelligent System Design and Engineering Application: *Voice based control for humanoid teleoperation*. Changsha, China.

MacDorman, K. F., & Ishiguro, H. (2006). The uncanny advantage of using androids in cognitive and social science research. *Interaction Studies, 7*(3), 297-337.

Manohar, V., Marzooqi, S. A., & Crandall, J. W. (2011). Proceedings from the 6th International Conference on Human-Robot Interaction: *Expressing emotions through robots: A case study using off-the-shelf programming interfaces*. Lausanne, Switzerland.

Marayong, P., Bettini, A., & Okamura, A. (2002). Proceedings from the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS): *Effect of virtual fixture compliance on human-machine cooperative manipulation*. Lausanne, Switzerland.

Marble, J. L., Bruemmer, D. J., & Few, D. A. (2003). Proceedings from the IEEE International Conference on Systems, Man and Cybernetics: *Lessons learned from usability tests with a collaborative cognitive workspace for human-robot teams.* Washington DC, USA.

Marin, R., Vila, P., Sanz, P. J., & Marzal, A. (2002). Proceedings from the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS): *Automatic speech recognition to teleoperate a robot via Web.* Lausanne, Switzerland.

Maulsby, D., Greenberg, S., & Mander, R. (1993). Proceedings from the INTERACT '93 and CHI '93 Conference on Human Factors in Computing Systems: *Prototyping an intelligent agent through Wizard of Oz*. Amsterdam, The Netherlands.

McRuer, D. T. (1995). Piolot-induced oscillations and human dynamic behavior (NASA Contractor Tech. Rep. 4683). Hawthorne, CA: National Aeronautics and Space Administration.

Meenink, H. C. M., Naus, G.J.L., Beelen, M.J., Steinbuch, M., Rosielle, P.C.J.N. & Smet, M.D. de. (2012). Proceedings from the Annual Meeting of the Association for Research in Vision and Ophthalmology: *Ex-vivo experiments with a microrobotic surgical system for vitreo-retinal surgery.* Fort Lauerdale, Florida.

Mehling, J. S., Strawser, P., Bridgwater, L., Verdeyen, W. K., & Rovekamp, R. (2007). Proceedings from the IEEE International Conference on Robotics and Automation (ICRA): *Centaur: NASA's mobile humanoid designed for field work.* Melanson, D. (2012). Roma, Italy.

Metta, G., Sandini, G., Natale, L., Craighero, L., & Fadiga, L. (2006). Understanding mirror neurons: A bio-robotic approach. *Interaction Studies, 7*(2), 197-232. doi:10.1075/is.7.2.06met

Michaud, F., Boissy, P., Labonté, D., Brière, S., Perreault, K., Corriveau, H., . . . Létourneau, D. (2010). Exploratory design and evaluation of a homecare teleassistive mobile robotic system. *Mechatronics*, 20(7), 751-766.

Miller, C., Funk, H., Wu, P., Goldman, R., Meisner, J., & Chapman, M. (2005). Proceedings from the Human Factors and Ergonomics Society 49th Annual Meeting: *The playbook approach to adaptive automation*. Orlando, Florida, USA.

Miller, C. A., & Parasuraman, R. (2003). Proceedings from the Human Factors and Ergonomics Society 47th Annual Meeting: *Beyond levels of automation: An architecture for more flexible human automation and collaboration*. Denver, Colorado.

Miller, C. A., Funk, H. B., Dorneich, M., & Whitlow, S. D. (2002). Proceedings from the 21st Digital Avionics Systems Conference: *A Playbook interface for mixed initiative control of multiple unmanned vehicles*. Irvine, CA.

Miller, N., Jenkins, O. C., Kallmann, M., & Mataric, M. J. (2004). Proceedings from the 4th IEEE/RAS International Conference on Humanoid Robots (ICRA): *Motion capture from inertial sensing for untethered humanoid teleoperation.* Barcelona, Spain.

Minsky, M. (1980). Telepresence. *Omni, 21*(45-51).

Moeslund, T. B., & Granum, E. (2001). A survey of computer vision-based human motion capture. *Computer Vision and Image Understanding, 81*, 231-268.

Moeslund, T. B., Hilton, A., & Krüger, V. (2006). A survey of advances in vision-based human motion capture and analysis. *Computer Vision and Image Understanding, 104*(203), 90-126.

Molin, L. (2004). Proceedings from the 3rd Nordic Conference on Human-Computer Interaction: *Wizard-of-Oz prototyping for co-operative interaction design of graphical user interfaces*. Tampere, Finland.

Montemerlo, M., & Thrun, S. (2007). *FastSLAM: A scalable method for the simultaneous localization and mapping problem in robotics*. Berlin/Heidelberg, Germany: Springer-Verlag.

Mori, M. (1970). The uncanny valley. *Energy, 7*(4).

Mukai, T., Nakashima, H., Sakaida, Y., & Guo, S. (2011). Realization and safety measures of patient transfer by nursing-care assistant robot RIBA with tactile sensors. *Journal of Robotics and Mechatronics, 23*(3), 360-369.

Mumm, J., & Mutlu, B. (2011). Proceedings from the 6th International Conference on Human-Robot Interaction: *Human-robot proxemics: Physical and psychological distancing in human-robot interaction*. Lausanne, Switzerland.

Murphy, R., Griffin, C. Stover, S. & Pratt, K. (2006). Proceedings from the IEEE Workshop on Safety, Security and Rescue Robots: *Use of micro air vehicles at Hurricane Katrina*. Gaithersburg, MD.

Murphy, R., Stover, S., Pratt, K., & Griffin, C. (2006). Proceedings from the IEEE Workshop on Safety, Security and Rescue Robots, IROS 2006 Video Session: Cooperative damage inspection with unmanned surface vehicle and micro unmanned aerial vehicle at Hurricane Wilma. Gaithersburg, MD.

Murphy, R. R. (2000). Marsupial and shape-shifting robots for urban search and rescue. *Intelligent Systems and their Applications, IEEE, 15*(2), 14-19. doi:10.1109/5254.850822

Murphy, R. R. (2004). Human-robot interaction in rescue robotics. *IEEE Transactions on Systems, Man, and Cybernetics: Part C— Applications and Reviews, 34*(2).

Nadel, J., Revel, A., Andry, P., & Gaussier, P. (2004). Toward communication: First imitation in infants, children with autism and robots. *Interaction Studies, 1*, 45-74.

NASA. (2012). R2 to ISS: Making a space worthy Robonaut. Retrieved from http://robonaut.jsc.nasa.gov/ISS/

Neo, E. S., Yokoi, K., Kajita, S., & Tanie, K. (2007). Whole-body motion generation integrating operator's intention and robot's autonomy in controlling humanoid robots. *IEEE Transactions on Robotics, 23*(4), 763-775. doi:10.1109/tro.2007.903818

Nielsen, C. W., Goodrich, M. A., & Ricks, B. (2007). Ecological interfaces for improving mobile robot teleoperation. *IEEE Transactions on Robotics, 23*(5), 927-941.

Olsen, D. R., & Wood, S. B. (2004). Proceedings from the ACM SIGCHI Conference on Human Factors in Computing Systems (CHI): *Fan-out: Measuring human control of multiple robots*. Vienna, Austria.

Parasuraman, R., Galster, S., Squire, P., Furukawa, H., & Miller, C. (2005). A flexible delegation-type interface enhances system performance in human supervison of multiple robots: Empirical studies with RoboFlag. *IEEE Transactions on Systems, Man, and Cybernetics—Part A: Systems and Humans, 35*(4), 481-493.

Parasuraman, R., Sheridan, T. B., & Wickens, C. D. (2000). A model for types and levels of human interaction with automation. *IEEE Transactions on Systems, Man, and Cybernetics, Part A, 30*(3), 286-297.

Park, J., & Khatib, O. (2006). A haptic teleoperation approach based on contact force control. *The International Journal of Robotics Research, 25*(5-6), 575-591.

Payandeh, S., & Stanisic, Z. (2002). Proceedings from the Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems: *On application of virtual fixtures as an aid for telemanipulation and training*. Orlando, Florida, USA.

Perzanowski, D., Schultz, A., Adams, W., Marsh, E., & Bugajska, M. (2001). Building a multimodal human-robot interface. *Intelligent Systems, 16*(1), 16-21.

Peterson, L., Austin, D., & Kragic, D. (2000). Proceedings from the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS): *High-level control of a mobile manipulator for door opening.* Takamatsu, Japan.

Petrovskaya, A., & Ng, A. Y. (2007). Proceedings from the 20th International Joint Conference on Artifical intelligence: *Probabilistic mobile manipulation in dynamic environments, with application to opening doors*. Hyderabad, India.

Quigley, M., Goodrich, M. A., & Beard, R. (2004). Proceedings from the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS): *Semi-autonomous human-UAV interfaces for fixed-wing mini-UAVs.* Sendi, Japan.

Randelli, G., Venanzi, M., & Nardi, D. (2011). Proceedings from the 6th International Conference on Human-Robot Interaction: *Tangible interfaces for robot teleoperation*. Lausanne, Switzerland.

Rani, P., Sarkar, N., Smith, C. A., & Adams, J. A. (2003). Proceedings from the IEEE International Conference on Systems, Man, and Cybernetics: *Anxiety detection for implicit human-machine interaction*. Washington DC, USA.

Reeves, B., & Nass, C. (1996). *The media equation: How people treat computers, television, and new media like real people and places*. New York: Cambridge University Press.

Rett, J., & Dias, J. (2007). Proceedings from the IEEE 10th International Conference on Rehabilitation Robotics (ICORR): *Human-robot interface with anticipatory characteristics based on Laban movement analysis and Bayesian models.* Noordwijk, the Netherlands.

Riek, L. D. (2012). The Wizard of Oz paradigm in human robot interaction: A systematic review. *Journal of Human-Robot Interaction, 1*(1).

Robins, B., Dautenhahn, K., & Dubowsky, J. (2005). Proceedings from the Social Intelligence and Interaction in Animals, Robots and Agents (AISB05): *Robots as isolators or mediators for children with autism? A cautionary tale*. Hatfield, UK.

Robins, B., Dautenhahn, K., & Dubowsky, J. (2006). Does appearance matter in the interaction of children with autism with a humanoid robot? *Interaction Studies, 7*(3), 479-512.

Robins, B., Dautenhahn, K., te Boerkhorst, R., & Billard, A. (2004). Effects of repeated exposure to a humanoid robot on children with autism. In S. Keates, Clarkson, J., Landong, P., & Robinson, P. (Eds.), *Designing a More Inclusive World* (pp. 225-236). London: Springer-Verlag.

Robins, B., Dickerson, P., Stribling, P., & Dautenhahn, K. (2004). Robot-mediated joint attention in children with autism: A case study in robot-human interaction. *Interaction Studies, 5*(2), 161-198.

Robins, B., & Dautenhahn., K. (2006). Proceedings from the 15th International Symposium on Robot and Human Ineractive Communication (RO-MAN06): *The role of the experimenter in HRI research—A case study evaluation of children with autism interacting with a robotic toy*. Hatfield, UK.

Rogalla, O., Ehrenmann, M., Zollner, R., Becher, R., & Dillmann, R. . (2002). Proceedings from the IEEE International Workshop on Robot and Human Interactive Communication: *Using gesture and speech control for commanding a robot assistant*. Berlin, Germany.

Roger, K., Guse, L., Mordoch, E., & Osterreicher, A. (2012). Social commitment robots and dementia. *Canadian Journal on Aging/ La revu canadienne du vieillissement, 31*(1), 87-94.

Roman, N., Wang, D., & Brown, G. J. (2003). Speech segregation based on sound localization. *Journal of the Acoustical Society of America, 114*(4), 2236-2252.

Rosenstein, M. T., Fagg, A. H., Platt Jr., R., Sweeney, J. D., & Grupen, R. A. (2005). Proceedings from the 20th National Conference on Artificial Intelligence: *Remote supervisory control of a humanoid robot*. (Vol. 20, No. 4, p. 1702). Menlo Park, CA; Cambridge, MA; London; AAAI Press; MIT Press; 1999.

Roth, P. M., & Winter, M. (2008). *Survey of appearance-based methods for object recognition*. Institute for Computer Graphics and Vision, Graz University of Techonology, Austria, Technical Report ICGTR0108 (ICG-TR-01/08).

Rungta, N., Brat, G., Clancey, W. J., Linde, C., Raimondi, F., Seah, C., & Shafto, M. (2013). Proceedings from the 3rd International Conference on Application and Theory of Automation in Command and Control (ATACCS). *Aviation safety: Modeling and analyzing complex interactions between humans and automated systems*. Naples, Italy. To appear.

Saffiotti, A., & Broxvall, M. (2005). Proceedings from the Joint Conference on Smart Objects and Ambient Intelligence: Innovative Context-Aware Services: Usages and Technologies: *PEIS ecologies: Ambient intelligence meets autonomous robotics*. Grenoble, France.

Sahbani, A., El-Khoury, S., & Bidaud, P. (2011). An overview of 3D object grasp and synthesis algorithms. *Robotics and Autonomous Systems, 60*(3), 326-336.

Sakamoto, D., Honda, K., Inami, M., & Igarashi, T. (2009). Proceedings from the 27th International Conference on Human Factors in Computing Systems: *Sketch and run: A stroke-based interface for home robots*. Boston, MA.

Sakamoto, D., Kanda, T., Ono, T., Ishiguro, H., & Hagita, N. (2007). Proceedings from 2nd ACM/IEEE International Conference on Human-Robot Interaction (RO-MAN): *Android as a telecommunication medium with a human-like presence*. Jeju Island, Korea.

Sandygulova, A., Campbell, A. G., Dragone, M., & O'Hare, G. M. P. (2012). Proceedings from the 7th ACM/IEEE International Conference on Human-Robot Interaction (HRI): *Immersive human-robot interaction.* Boston, Massachusetts, USA.

Sangbae, K., Hawkes, E., Kyujin, C., Joldaz, M., Foleyz, J., & Wood, R. (2009). Proceedings from the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS): *Micro artificial muscle fiber using NiTi spring for soft robotics.* St. Louis, Missouri, USA.

Satkin, S., Lin, J., & Hebert, M. (2012). Proceedings from the 23rd British Machine Vision Conference: *Data-driven scene understanding for 3D models*. Surrey, United Kingdom.

Scassellati, B. (2005). Proceedings from the 12th International Symposium of Robotics Research: *How social robots will help us to diagnose, treat, and understand autism*. San Francisco, CA.

Scassellati, B., Admoni, H., & Mataric, M. (2012). Robots for use in autism research. *Annual Review of Biomedical Engineering, 14*(1), 275-294. doi:10.1146/annurev-bioeng-071811-150036

Schaal, S. (2007). The new robotics—Towards human-centered machines. *HFSP Journal, 1*(2), 115-126.

Scholtz, J., Theofanos, M., & Antonishek, B. (2002). Proceedings from the 36th International Conference on System Sciences: *Theory and evaluation of human robot interactions*. Hawaii.

Sharkey, A., & Sharkey, N. (2012). Granny and the robots: Ethical issues in robot care for the elderly. *Ethics and Information Technology, 14*(1), 27-40. doi:10.1007/s10676-010-9234-6

Sheridan, T. B. (1992). *Telerobotics, automation, and human supervisory control*. MIT Press. Cambridge, Massachusetts, USA.

Sheridan, T. B., & Verplank, W. L. (1978). *Human and computer control for undersea teleoperators.* MIT Man-Machine Systems Laboratory. Cambridge, Massachusetts, USA, Technical Report.

Shin, D., Sardellitti, I., Park, Y.-L., Khatib, O., & Cutkosky, M. (2010). Design and control of a bio-inspired human-friendly robot. *The International Journal of Robotics Research, 29*(5), 571-584. doi: 10.1177/0278364909353956

Shiomi, M., Kanda, T., Glas, D. F., Satake, S., Ishiguro, H., & Hagita, N. (2009). Proceedings from the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS): *Field trial of networked social robots in a shopping mall.* St. Louis, Missouri, USA.

Short, E., Hart, J., Vu, M., & Scassellati, B. (2010). Proceedings from the 5th ACM/IEEE International Conference on Human-Robot Interaction: *No fair!! An interaction with a cheating robot*. Osaka, Japan.

Sian, N. E., Yokoi, K., Kajita, S., Kanehiro, F., & Tanie, K. (2002). Proceedings from the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS): *Whole body teleoperation of a humanoid robot—Development of a simple master device using joysticks.* Lausanne, Switzerland.

Smallman, H. S., & John, M. S. (2005). Naive realism: Misplaced faith in the utility of realistic displays. *Ergonomics in Design: The Quarterly of Human Factors Applications, 13*(3), 6-13.

Smith, R.C. & Cheeseman, P. (1986). On the representation and estimation of spatial uncertainty. *The International Journal of Robotics Research* 5(4): 56–68.

Sokho, C., Jungtae, K., Insup, K., Jin Hwan, B., Chongwon, L., & Jong Oh, P. (1999). Proceedings from the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS): *KIST teleoperation system for humanoid robot.* Takamatsu, Japan.

Space Teleorobotics (ANOTHER CHAPTER IN THIS COLLECTION).

Spudis, P. D. T., G. J. (1992). Proceedings from the Second Conference on Lunar Bases and Space Activities of the 21st Century: *The roles of humans and robots as field geologists on the moon*. NASA Johnson Space Center, Houston, Texas, USA.

Squire, P., Trafton, G., & Parasuraman, R. (2006). Proceedings from the ACM/IEEE International Conference on Human-Robot Interaction: *Human control of multiple unmanned vehicles: Effects of interface type on execution and task switching times*. Salt Lake City, UT.

Stiefelhagen, R., Fugen, C., Gieselmann, R., Holzapfel, H., Nickel, K., & Waibel, A. (2004). Proceedings from the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS): *Natural human-robot interaction using speech, head pose and gestures*. Sendai, Japan.

Stone, R. J. (2000). Proceedings from the 1st International Workshop on Haptic Human-Computer Interaction: *Haptic feedback: A brief history from telepresence to virtual reality*. Glasgo, UK.

Sumpter, D. J. T. (2006). The principles of collective animal behavior. *Philosophical Transactions of the Royal Society B: Biological Sciences, 361*, 5-22.

Sun, Y., & Nelson, B. J. (2002) Biological cell injection usin an autonomous microrobotic system. *International Journal of Robotics Research*. 21(10-11), 868-868.

Sung, J., Grinter, R. E., & Christensen, H. I. (2009). Proceedings from the 27th International Conference on Human Factors In Computing Systems: *"Pimp My Roomba": Designing for personalization*. Boston, MA.

Sutera, S., Pandey, J., Esser, E. L., Rosenthal, M. A., Wilson, L. B., Barton, M., . . . Fein, D. (2007). Predictors of optimal outcome in toddlers diagnosed with autism spectrum disorders. *Journal of Autism and Devopmental Disorders, 37*(1), 98-107. doi:10.1007/s10803-006-0340-6

Sycara, K., & Lewis, M. (2012). Proceedings from the the 16th WSEAS Interantional Conference on Computers: *Human control strategies for multi-robot teams*. Kos Island, Greece.

Syrdal, D. S., Walters, M. L., Otero, N., Koay, K. L., & Dautenhahn, K. (2007). Proceedings from the AAAI-07 Workshop W06 on Human Implications of Human-Robot Interaction: *"He knows when* *you are sleeping"—Privacy and the personal robot companion.* Vancouver, British Columbia, Canada.

Tachi, S., Komoriya, K., Sawada, K., Nishiyama, T., Itoki, T., Kobayashi, M., and Inoue, K. (2003). Telexistance cockpit for humanoid robot control. *Advanced Robotics, 17*(3), 199-217.

Takayama, L., Groom, V., & Nass, C. (2009). Proceedings from the 27th International Conference on Human Factors in Computing Systems: *I'm sorry, Dave: I'm afraid I won't do that: Social aspects of human-agent conflict*. Boston, MA.

Tapus, A., Mataric, M. J., & Scasselati, B. (2007). Socially assistive robotics [Grand challenges of robotics]. *Robotics & Automation Magazine, IEEE, 14*(1), 35-42. doi:10.1109/mra.2007.339605

Tapus, A., Tapus , C., & Mataric, M. J. (2008). User-robot personality matching and assistive robot behavior adaptation for post-stroke rehabilitation therapy. *Intelligent Service Robotics, 1*(2), 169-183. doi:10.1007/s11370-008-0017-4

Tapus, A., Tapus, C., & Mataric, M. J. (2009). Proceedings from the IEEE International Conference on Rehabilitation Robotics (ICORR): *The use of socially assistive robots in the design of intelligent cognitive therapies for people with dementia.* Zurich, Switzerland.

Thomaz, A. L., & Breazeal, C. (2008). Teachingable robots: Understanding human teaching behavior to build more effective robot learners. *Artificial intelligence Journal, 172*, 716-737.

Thrun, S., Bennewitz, M., Burgard, W., Cremers, A. B., Dellaert, F., Fox, D., . . . Schulz, D. (1999). Proceedings from the IEEE International Conference on Robotics and Automation: *MINERVA: A second-generation museum tour-guide robot.* Detroit, Michigan, USA.

Timmermans, A. A., Seelen, H. A., Willmann, R. D., & Kingma, H. (2009). Technology-assisted training of arm-hand skills in stroke: Concepts on reacquisition of motor control and therapist guidelines for rehabilitation technology design. *Journal of Neuroengineering and Rehabilitation, 6*, 1-6.

Tomatis, N., Mayor, L., Drygajlo, A., & Siegwart, R.. (2005). Robots meet Humans-interaction in public spaces. *IEEE Transactions on Industrial Electronics.* 52(6): 1530-1546.

Torta, E., Oberzaucher, J., Werner, F., Cuijpers, R.H. & Juola, J.F. (2013). Attitudes toward socially assistive robots in intelligent homes: Results from laboratory studies and field trials. *Journal of Human-Robot Interaction*. 1(2), 76-99.

Trafton, J. G., Schultz, A. C., Perznowski, D., Bugajska, M. D., Adams, W., Cassimatis, N. L., and Brock, D. P. (2006). Proceedings of the 1st ACM International Conference on Human-Robot Interaction: *Children and Robots Learning to Play Hide and Seek.* Salt Lake City, Utah, USA.

Trivedi, D., Rahan, C. D., Kier, W. M., & Walker, I. D. (2008). Soft robotcs: Biological inspiration, state of the art, and future research. *Applied Bionics and Biomechanics, 5*(3), 99-117.

Tsui, K. M., Desai, M., & Yanco, H. A. (2010). Proceedings from the 5th ACM/IEEE International Conference on Human-Robot Interaction: *Considering the bystander's perspective for indirect human-robot interaction*. Osaka, Japan.

Valin, J.-M., Michaud, F., & Rouat, J. (2007). Robust localization and tracking of simultaneous moving sound sources using beamforming and particle filtering. *Robotics and Autonomous Systems*, 55(3), 216-228.

Valin, J.-M., Yamamoto, S., Rouat, Jean, Michaud, F., Nakadai, K., & Okuno, H.G., (2007). Robust recognition of simultaneous speech by a mobile robot. *IEEE Transactions on Robotics.* 23(4), 742-752.

Veruggio, G., Solis, J., & Van der Loos, M., Eds. (2011). Robo ethics: Defining responsibility to protect humankind. *IEEE Robotics and Automation Magazine, 18*(1).

Vlasic, D., Adelsberger, R., Vannucci, G., Barnwell, J., Gross, M., Matusik, W., & Popovic, J. (2007). Proceedings from the ACM Transactions on Graphics (TOG) SIGGRAPH: *Practical motion capture in everyday surroundings*. San Diego, CA.

Vondrak, M., Sigal, L., Hodgins, J., & Jenkins, O. (2012). Proceedings from the ACM Transactions on Graphics (TOG) SIGGRAPH: Video-based 3D motion capture through biped control.

Voyles, R. (1997). *Toward gesture-based programming: Agent-based haptic skill acquisition and interpretation.* (Doctoral Dissertation, Tech. Rep. CMU-RI-TR=97-36). Pittsburg, PA: Robotics Institute, Carnegie Mellon University.

Wade, E., Parnandi, A. R., & Mataric, M. J. (2011). Proceedings from the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS): *Using socially assistive robotics to augment motor task performance in individuals post-stroke.* San Francisco, California, USA.

Walker, A. M., & Miller, D. P. (2012). Proceedings from the 7th Annual ACM/IEEE International Conference on Human-Robot Interaction: *Tele-operated robot control using attitude aware smartphones*. Boston, MA.

Walters, M. L., Dautenhahn, K., te Boekhorst, R., Kheng Lee, K., Kaouri, C., Woods, S., . . . Werry, I. (2005). Proceedings from the IEEE International Workshop on Robot and Human Interactive Communication (RO-MAN): *The influence of subjects' personality traits on personal spatial zones in a human-robot interaction experiment.* Nashville, Tennessee, USA.

Walters, M. L., Dautenhahn, K., Woods, S. N., & Koay, K. L. (2007). Proceedings from the ACM/IEEE International Conference on Human-Robot Interaction: *Robotic etiquette: Results from user studies involving a fetch and carry task*. Arlington, VA.

Weiss, A., Igelsböck, J., Tscheligi, M., Bauer, A., Kuhnlenz, K., Wolherr, D., & Buss, M. (2010). Proceedings from the 5th ACM/IEEE International Conference on Human-Robot Interaction: *Robots asking for directions: The willingness of passers-by to support robots*. Osaka, Japan.

Whetten, J. M., Goodrich, M. A., & Guo, Y. (2010). Proceedings from the IEEE International Conference on Systems, Man, and Cybernetics: *Beyond robot fan-out: Towards multi-operator supervisory control*. Istanbul, Turkey.

Wikipedia. (2012a). AI Winter. Retrieved from http://en.wikipedia.org/wiki/AI_winter

Wikipedia. (2012b). BigDog. Retrieved from http://en.wikipedia.org/wiki/BigDog.

Wikipedia. (2012c). Motion Capture. Retrieved from http://en.wikipedia.org/wiki/Motion_capture

Wikipedia. (2012d). Nao (robot). Retrieved from http://en.wikipedia.org/wiki/Nao_(robot)

Woods, D. D., Tittle, J., Feil, M., & Roesler, A. (2004). Envisioning human-robot coordination in future operations. *IEEE Transactions on Systems, Man, and Cybernetics, Part A, 34*(6), 749-756.

Wousheng, C., Tianmiao, W., & Lei, H. (2003). Proceedings from the 11th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (HAPTICS'03): *Design of data glove and arm type haptic interface*. Los Angeles, California, USA.

Yamane, K., Hodgins, J. K., & Brown, H. B. (2004). Controlling a motorized marionette with human motion capture data. *International Journal of Humanoid Robots, 1*(4), 651-669.

Yan, W., Torta, E., van der Pol, D., Meins, N., Weber, C., Cuijpers, R. H. & Wermter, S. (2012). Learning robot vision in ambient homes. In J. C. García-Rodríguez, M. (Ed.), *Robotic Vision: Technologies for Machine Learning and Vision Applications*: Hershey, PA: IGI Global.

Yamamoto, S.; Nakadai, K.; Nakano, M.; Tsujino, H.; Valin, J.-M.; Komatani, K.; Ogata, T.; Okuno, H.G., (2007). Proceedings from the IEEE Workshop on Automatic Speech Recognition and Understanding. *Design and implementation of a robot audition system for automatic speech recognition of simultaneous speech*. Kyoto, Japan.

Yim, M. (2006). Proceedings from the AAAI Spring Symposium: To Boldly Go Where No Human-Robot Team Has Gone Before: *Astronauts must program robots*. Menlo Park, CA.

Yokoyama, K., Handa, H., Isozumi, T., Fukase, Y., Kaneko, K., Kanehiro, F., . . . Hirukawa, H. (2003). Proceedings from the IEEE International Conference on Robotics and Automation (ICRA '03): *Cooperative works by a human and a humanoid robot.* Taipei, Taiwan.

Zhao, W., Chellappa, R., Phillips, P. J., & Rosenfeld, A. (2003). Face recognition: A literature survey. *ACM Computing Surveys, 35*(4), 399-458. doi:10.1145/954339.954342