Introduction to the Special Issue on Human–Robot Interaction

I. Introduction

THE growing importance of human–robot interaction (HRI) is clearly demonstrated by the growing number of individuals focusing their research in this area, the inclusion of paper and panel sessions at nonrobotics focused conferences such as the IEEE International Conference on Systems, Man, and Cybernetics and Human Factors meetings, as well as this being the third special issue on the topic in the last two years [1], [2]. In addition to the existing annual IEEE Workshop on Robot and Human Interactive Communication (RO-MAN), the First Annual Conference on Human–Robot Interaction (HRI'06) will take place in March 2006 [3]. HRI'06 seeks to create an inherently interdisciplinary venue for experts in HRI, human factors, ergonomics, and human–computer interaction.

HRI research is not new. Initially, the work was driven by the need to handle hazardous radioactive materials [4]. Human–robot interfaces began in the form of teleoperation of robotic arms that were mechanically intricate but limited by the lack of sensing and reasoning capabilities. Through a one-way communication using a hand controller, the robot was viewed as an extension of the human body. It provided the equivalent of a long arm that could safely reach into the hazardous area without harming the operator. In industry applications, robotic manipulators were directed using teach pendants. This form of teleoperation was used to store a control program by directing the robot through a sequence of positions and actions, such as pick up an object here and place it there. In both cases, it was assumed that the human operator provided the intelligence necessary to perform the activity. The robot was merely following (blindly) the actions directed by its operator.

In the case of teleoperation for manipulation of objects, often critical in the handling of hazardous materials, operators noted the lack of feeling in the controls. The lack of touch and kinesthetic feel limited the ability to perform manipulative tasks. Researchers addressed the limitation by developing hand controllers that incorporated force reflection back to the operator in an effort to make the teleoperation easier and more natural [5].

Over the years, many related fields have influenced the nature of human–robot interfaces. As research advances were made in sensing techniques, increased computational capabilities, new control paradigms, new methods in artificial intelligence, as well as advances in human–computer interaction and computer graphics, the human–robot interface changed to accommodate the new possibilities. These outside influences have given the field an inherently multidisciplinary feel.

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In the 1960s, supervisory control was introduced as an alternative control method to the direct manipulation of teleoperation [6], [7]. The robot was given some autonomy in being able to automatically control some aspect of its own operation. The operator could then issue a few discrete, high-level commands that were translated into a series of low-level joint commands. This relieved the operator from the demands of continuously driving the robot.

In the paradigm of shared control (e.g., used in [8]), the robot could be assigned control of one or more degrees of freedom while the operator directed the rest of the motion. Today, we see evidence of this type of control in the cruise control of cars, which controls the speed of driving, while the driver controls the steering. A sophisticated form is also used in the autopilot of airplanes, which can control altitude, attitude, vertical speed, and heading.

Work in computer graphics has facilitated a different kind of interface. Using graphical models and simulation, virtual environments have been created as a front-end interface for controlling a robot [9], [10]. These graphical interfaces provided visual cues and constraints and also allowed the operator to try out a trajectory in a virtual setting before sending it to a real robot for execution. The display could be used to show a different view, or the display could be used to show predicted motion of the operator's commands, as a means of overcoming transmission delays, e.g., from ground control to robots in outer space [11]. Later, virtual environments provided a sophisticated method to program the robot by showing the desired actions in a simulated environment [12]. The physical robot was not even required. (See, for example, [13] in this issue.)

As new sensors became available, they were added to the robot and provided the opportunity to convey additional information back to the user. In particular, force sensing and touch sensing have been studied for integration into human–robot interfaces. Much work has been done to study haptic sensing in the human perceptual system and to develop devices that measure force and contact of both rigid and deformable objects [14]–[17]. Haptic information has also been used in Programming by Demonstration systems for both physical and virtual environments [18]–[20]. Today, haptic information is being studied for medical robots [21]–[23].

As work progressed on robot manipulators, parallel research was addressing the challenge of mobile robots. Initially, much of the research on mobile robots was guided by the goal of achieving autonomous robots. Although progress was made in this endeavor, researchers gradually began to realize that semiautonomous mobile robots, guided in part by human operators, could provide useful and more realistic functionality. Adams [24] developed the multiple agent supervisory control system and the underlying mediation hierarchy for a multiple mobile robot system designed for indoor material handling tasks [25]. Since this early work, a compelling application has emerged in the urban search-and-rescue (USAR) context. Mobile robots are teleoperated (using a remote display of the robot camera) into disaster areas of fallen buildings to search for victims and survivors [26]. More recent work has focused on developing collaborative interaction [27], shared control [28], and supervised autonomy [29].

The addition of autonomy into robots, as well as new interface modalities has opened the door to more interactive, two-way communication with robots. New interface modalities include the use of speech [30]–[32], gestures [33], sketches [34], [35], and emotions [36]. Adding intelligence techniques into robots has now opened up the possibility of social robots with more human-like interfaces which may interact in subtle ways using typical nonverbal human communication, such as an exchange of facial expressions, the tilt of the head, or a shift in gaze which directs the focus [37]–[39].

One might argue that the most effective HRI research has been motivated by a specific application and was addressed as a systems-level effort. Much of the early work took an engineering perspective on the robot and the interface mechanics instead of a user perspective. The human factors field has repeatedly shown the importance of starting interface design and development from the user perspective rather than the engineering perspective. This implies that the interface is developed based upon application needs of the user while considering limitations such as cognitive or mental workload, situational awareness, decision making, fatigue, and stress [40].

In addition to understanding the user perspective and considering the associated limitations, continuous user feedback is required throughout the design and development phases. Since many novice users have unrealistic expectations of robot capabilities, users must be educated to understand the limitations of robotic systems, and such limitations must also be considered in the interface design. These additional considerations require a systems-level approach to HRI development.

The need to move the development focus from the engineering perspective to the system and user perspectives inherently imply that evaluations based on human factors are necessary. Adams' early work has been cited as "... one of the earliest formal usability studies conducted on robotic software..." [41]. However, until recently, few formal evaluations have been conducted.

Since the late 1990s, the HRI field has gained momentum; however, evaluation techniques and the application of the techniques have been slow to emerge. Thus, the focus of this special issue is on papers that either present new evaluation methodologies (see [42] and [43]) or has employed qualitative (see [44] and [45]) or quantitative (see [13] and [46]–[50]) user feedback and evaluation methods.

II. Special Issue

In total, 47 papers were received in response to the call for papers, almost twice as many as anticipated. These contributions came from around the world and ranged from teleoperation-based systems to robot-assistive technologies. The large number of papers created an arduous review task. Initially, the papers were reviewed to determine which papers address the issue's focus on user evaluation methodologies and application. Each of the remaining papers received three reviews (one from a human factors expert and two from HRI experts). The results of the review process are the ten papers you find in this special issue. Two of the papers are focused on methodology development, and two papers are focused on qualitative evaluation techniques. The remaining six papers each employ quantitative evaluations focused on multiple robot systems, visual-based interface augmentation, and teleoperation.

Crandall *et al.* [42] present a validation of their neglect tolerance methodology for multitasking environments. The neglect tolerance methodology focuses on the amount of time a robot can be ignored before the associated performance begins to fall (neglect time) and the required time that the human must interact with the robot to return it to peak performance (interaction time). The authors are exploring the use of neglect tolerance for determining the maximum number of robots that can be managed, feasible multiple robot configurations, and predicting multiple robot team performance under certain conditions.

Many methods have been developed in human factors that measure situational awareness; however, Scholtz *et al.* [43] focus on developing a methodology specific to robotic systems. The author's intent is to develop a tool that can be applied across robotic systems to ensure accurate comparisons between interfaces. This tool will permit a comparison of the user's situational awareness. The paper presents the initial assessment tool as well as revisions to the tool based upon three user evaluations.

The first qualitative evaluation by Trafton *et al.* [44] focuses on understanding human perspective-taking, employing cognitive modeling and applying the results to human–robot interaction. They evaluate perspective-taking in a natural environment based upon astronaut interactions and incorporate the results into their perspective-taking cognitive architecture, Polyscheme. The authors also present robot experiments employing Polyscheme.

Michaud *et al.* [45] have focused on developing a spherical robot for child development, in particular, for very young children. The authors have developed an autonomous spherical robot, Roball, that provides motion, messages, sounds, and illumination to interact with young children. The authors present the Roball design and the qualitative evaluation they conducted with children between the ages of 12 and 24 months. It is hypothesized that Roball can improve a young child's motor, intellectual, social, affective, and language skills.

Parasuraman *et al.* [46] present a series of three quantitative experiments that investigate the effects of delegation-type interfaces for simulated, multiple unmanned vehicles. The presented interface is a simplified version of Playbook. The evaluations spanned various levels of autonomy and compared delegation interfaces to more restricted interfaces. The primary result is initial empirical evidence representing the efficacy of employing delegation-based interfaces for supervising multiple robots.

Bruemmer *et al.* [47] describe a mixed-initiative HRI for indoor search and exploration tasks with corresponding evaluation results. The authors have developed the INL Robot Intelligence Architecture that permits multiple robots to have multiple behaviors and levels of autonomy. An associated HRI has also been developed. The initial HRI has a two-dimensional (2-D) interface, but the authors also introduce and test a three-dimensional (3-D) interface. Three evaluations were conducted that required participants to interact with a robot in a remote search environment that included office dividers, mannequins, a disabled robot, and a simulated explosive device. The evaluations were designed to assess operator workload and error along with overall performance.

The papers provided by Kanduri *et al.* [48] and Hughes and Lewis [49] both focus on understanding imagery and its application to HRI. Kanduri *et al.* focus on providing the operator with accurate and understandable geometry and scale information from the robot's environment. The authors present an evaluation focused on measuring an observer's ability to estimate height of distant objects when provided with an accurate local model of the robot, a panoramic image and a physical mock-up of the local terrain. Two estimation techniques were incorporated into the evaluation.

Hughes and Lewis [49] are also concerned with the presentation of imagery to the operator. In particular, they focus on assessing the effectiveness of existing and potential teleoperation controls for cameras. Most camera systems are poorly placed on the robot with a narrow field of view. Camera properties can also significantly impair the operator's ability to perceive the environment. One important finding from their work suggests that controlling the camera independently from the vehicle orientation may provide benefits.

Tsuji and Tanaka [50] analyze the changes of the tracking control properties of a human–robot system with regard to robot impedance, operator proficiency, and the impedance properties of the human arm. The paper explores the control characteristics of the human operator according to robot impedance properties. An evaluation was conducted to demonstrate humans' ability to constantly maintain the dynamic properties of the system by adjusting their own impedance properties.

The final paper by Aleotti *et al.* [13] investigates various types of virtual fixtures for a programming by demonstration interface for teleoperation. The system evaluations employ peg-in-hole tasks. The authors evaluate the effectiveness of color, sound, and tactile fixtures for teleoperation. The interface employs a CyberTouch VR glove coupled with the virtual environment display. The authors found that tasks that were perceived as difficult but included virtual fixtures of any type lead to longer times but result in more successful task completions.

As can be seen from these short summaries, the special issue covers a broad spectrum of topics but the underlying theme is the evaluation of HRI systems. The evaluation papers present some interesting and important HRI development insights. The methodology papers take important steps toward defining tools that can be applied to accurately assess HRI techniques and methodologies.

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JULIE A. ADAMS, *Guest Editor*
Electrical Engineering and
Computer Science Department
Vanderbilt University
Nashville, TN 37067 USA
julie.a.adams@vanderbilt.edu

MARJORIE SKUBIC, *Guest Editor*
Electrical and Computer
Engineering Department
University of Missouri
Columbia, MO 65211 USA
skubicm@missouri.edu

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Julie A. Adams (M'91–SM'01) received the M.S.E. and Ph.D. degrees in computer and information sciences from the University of Pennsylvania, Philadelphia, in 1993 and 1995, respectively.

She is an Assistant Professor of computer science in the Electrical Engineering and Computer Science Department, Vanderbilt University, Nashville, TN. She began her academic career as an Assistant Professor of computer science at Rochester Institute of Technology, Rochester, NY, in 2000. Prior to her academic career, she worked in human factors for Honeywell, Inc. and the Eastman Kodak Company for five years. She has authored over 35 publications and has received funding from the National Science Foundation. Her current research interests include human–robot interaction and distributed intelligent algorithms for large multiple robot teams. Her current research projects focus on autonomous coalition formation and the development of human-interaction techniques for human–robot teams conducting search-and-rescue activities.

Prof. Adams is a Member of the Human Factors and Ergonomics Society, the Association of Computing Machinery, and the American Associate of Artificial Intelligence. She is the Vice President of Long Range Planning and Finance for the IEEE Systems, Man, and Cybernetics Society (SMCS). She has held various positions within the SMCS. She has also served as a member of the IEEE Technical Activities Board Finance Committee and Society Review Committee. She is the Local Arrangements Chair for the IEEE 2005 Workshop on Robot–Human Interactive Communication (RO-MAN) and the Finance Chair for the First Annual Conference on Human–Robotic Interaction. She also organized the Human–Robotic Interaction track at the 2003 IEEE International Conference on Systems, Man, and Cybernetics.

Marjorie Skubic (M'97) received the Ph.D. degree in computer science from Texas A&M University, College Station, in 1997

She is an Associate Professor of electrical and computer engineering at the University of Missouri, Columbia, with a joint appointment in computer science. She has authored over 60 publications and has received funding from the National Science Foundation, the U.S. Naval Research Laboratory, and the U.S. Army. In addition to her academic experience, she has spent 14 years working in industry for companies such as TRW, Texas Instruments, and Staefa Control Systems, in real-time applications such as data acquisition and automation. Her current research interests include sensory perception, computational intelligence, and human–robot interaction. She has been working on novel interfaces for robots such as interfaces based on sketching and human-like spatial language. Her newest project is a study on sensory perception for eldercare technology. She has a special interest in using robots for educational purposes.

Dr. Skubic is a Past Co-Chair of the Education Committee of the IEEE Robotics and Automation Society. She is currently the Program Co-Chair of the IEEE 2005 Workshop on Robot–Human Interactive Communication (RO-MAN).