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Human–Robot Interaction: Status and Challenges

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Objective: The current status of human–robot interaction (HRI) is reviewed, and key current research challenges for the human factors community are described.

Background: Robots have evolved from continuous human-controlled master–slave servomechanisms for handling nuclear waste to a broad range of robots incorporating artificial intelligence for many applications and under human supervisory control.

Methods: This mini-review describes HRI developments in four application areas and what are the challenges for human factors research.

Results: In addition to a plethora of research papers, evidence of success is manifest in live demonstrations of robot capability under various forms of human control.

Conclusions: HRI is a rapidly evolving field. Specialized robots under human teleoperation have proven successful in hazardous environments and medical application, as have specialized telerobots under human supervisory control for space and repetitive industrial tasks. Research in areas of self-driving cars, intimate collaboration with humans in manipulation tasks, human control of humanoid robots for hazardous environments, and social interaction with robots is at initial stages. The efficacy of humanoid general-purpose robots has yet to be proven.

Applications: HRI is now applied in almost all robot tasks, including manufacturing, space, aviation, undersea, surgery, rehabilitation, agriculture, education, package fetch and delivery, policing, and military operations.

Keywords: robot, human interaction, supervisory control, research needs, teleoperator, telerobot

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INTRODUCTION

Human–robot interaction (HRI) is currently a very extensive and diverse research and design activity. The literature is expanding rapidly, with hundreds of publications each year and with activity by many different professional societies and ad hoc meetings, mostly in the technical disciplines of mechanical and electrical engineering, computer and control science, and artificial intelligence. Every year since 2006, the IEEE has hosted a specialists symposium on human–robotic interaction (IEEE Robotics and Automation Society, 2015). Goodrich and Schultz (2007) provide an excellent though slightly dated survey of the literature.

While human–automation interaction, for example, in piloting aircraft, has long been an active issue in human factors, to date, HRI has been relatively neglected by our community though embraced by others identifying with, for example, human–computer interaction. In any case, the needs for research on human interaction aspects and participation in robot research and design are huge. Human factors professionals can obviously benefit by improved understanding of dynamics, control, and computer science (artificial intelligence) but at least should find ways to collaborate with engineers in these fields in research, conceptual design, and evaluation.

HRI can be divided roughly into four areas of application:

1. Human supervisory control of robots in performance of routine tasks. These include handling of parts on manufacturing assembly lines and accessing and delivery of packages, components, mail, and medicines in warehouses, offices, and hospitals. Such machines can be called *telerobots*, capable of carrying out a limited series of actions automatically, based on a computer program, and capable of sensing its environment and its own joint positions and communicating such information back to a human operator who updates its computer instructions as required.

2. Remote control of space, airborne, terrestrial, and undersea vehicles for nonroutine tasks in hazardous or inaccessible environments. Such machines are called *teleoperators* if they perform manipulation and mobility tasks in the remote physical environment in correspondence to continuous control movements by the remote human. If a computer is intermittently reprogrammed by a human supervisor to execute pieces of the overall task, such a machine is a *telerobot.*
3. Automated vehicles in which a human is a passenger, including automated highway and rail vehicles and commercial aircraft.
4. Human–robot social interaction, including robot devices to provide entertainment, teaching, comfort, and assistance for children and elderly, autistic, and handicapped persons.

In each of the four areas, I cite some background, describe exemplary ongoing research, and discuss research challenges.

The article then includes a section on generic human factors research needs, that is, fundamental "hard problems" of HRI that are common to two or more aforementioned areas.

Human Supervisory Control of Robots for Routine Industrial Tasks

There is a huge variety of robots doing assembly line tasks: picking and placing, welding, painting, and so on. Readers are surely aware of production lines for automobiles and other products that seem entirely robotized. To the extent that human operators are required for the functions of supervisory control (planning, teaching, monitoring of automatic control, making repairs, and learning from experience), such machines are telerobots (Sheridan, 1992).

The Baxter assembly line robot is a marketed product by Rethink Robotics in Boston. It is a widely discussed robot designed to be safe to operate in close proximity with people because it is mechanically compliant, much like the human body. An interesting innovation in the Baxter robot is a displayed set of eyes not for the robot to see but rather for it to communicate to the human operator a sense of what the robot's program is currently attending to. Also, Baxter's arms can be made mechanically compliant, enabling a programmer to move its hand as part of teaching it a manipulation task or working in close proximity to people.

With the aim of improving human–robot side-by-side interactions in industrial settings, such as aircraft assembly, Shah, Wiken, Williams, and Breazeal (2011) and Gombolay, Huang, and Shah (2015) have demonstrated techniques for observing human subjects in performing a manipulation task. Observation is done by using markers on the human limbs seen by computer vision. That information is used to infer a robust policy for close collaboration with a robot by relieving the human of certain task elements that a robot can perform more efficiently. The technique can also differentiate task style of human workers. In an experiment, Shah et al. found that subjects preferred having the robot anticipate their actions as compared with manually ordering the robot to take over certain task elements. The subjects also judged the technique to be superior to having a domain expert program the allocation of responsibility.

Current HRI challenges for routine tasks extend well beyond the factory assembly line for fetching and delivery of parts and packages (e.g., as used by Amazon warehouses), mail pickup and delivery in office buildings, fetching and delivery of medicine and supplies in hospitals, floor cleaning, and automated agricultural tasks. Safety (collision avoidance) is a continuing issue (Vasic & Billard, 2013). The greatest human factors research needs are in planning, teaching, display, control, and supervisor monitoring of automatic action.

Teleoperation/Telerobotics in Hazardous or Inaccessible Environments

The era of robotics began with a human performance need: how to manipulate highly radioactive objects without exposing the human operator. In the late 1940s, Raymond Goertz at Argonne National Laboratory built master–slave remote handling devices by means of which one could grasp and move objects in all six degrees of freedom (Corliss & Johnsen, 1968; Vertut & Coiffet, 1984). At first, the coupling between the human operator's master control and the slave arm-hand was by means of mechanical tapes, but later this coupling employed electromechanical servomechanisms with force feedback. Goertz

kindly gave the Massachusetts Institute of Technology (MIT) two of the latter systems, one of which was used by Heinrich Ernst (1961) in what I would assert was the first computer-controlled robot; the second was used in my lab for early experiments on human–robot supervisory control (Brooks, 1979: Ferrell & Sheridan, 1967). Figure 1 illustrates one such early device.

Much progress has been made in remote control of unmanned spacecraft (Skaar & Ruoff, 1994), undersea robotic vehicles (Sheridan & Verplank, 1978), and unmanned aerial vehicles, or UAVs (Burke & Murphy, 2010). Human factors research continues to be needed for improving and simplifying display and control interfaces. Two particular problems with human factors implications are (a) provision of 360° observation at the remote site and (b) compensation for intermittent communication delays and dropouts.

There are promising developments in using robotic avatars for surveillance, search and rescue for police work, border patrol, firefighting and rescue, and military operations (Barnes & Jentsch, 2010), with many human factors issues for display and control and mental workload (Murphy & Peschel, 2013; Murphy et al., 2008).

The recently completed Defense Advanced Research Projects Agency (DARPA) International Robot Challenge characterizes the state of the art with respect to general-purpose telerobots. Having in mind a humanoid telerobot that could perform a variety of functions for a disaster situation too dangerous for direct human participation, such as the Fukushima nuclear meltdown, DARPA had each telerobot compete on six tasks (see "DARPA Robotics Challenge" in Wikipedia for numerical results for each task). These tasks included climbing stairs, operating a rotary valve, opening a door and walking through, stepping across rubble, sawing a piece out of plasterboard with a hand tool, and getting in and out of a vehicle. Nineteen contestants were scored on task success and performance time. The DARPA sponsors purposely constrained the bandwidth of communication between telerobot and human controller so that continuous teleoperation was impossible; computer task execution under supervisory control was therefore essential. Not all entrants could do all tasks, and some telerobots fell and could not get themselves up (see https://www.youtube.com/watch?v=g0TaYhjpOfo). Figure 2 shows the winner from the Korean Institute of Science and Technology, KAIST (which cleverly had legs with supplementary wheels attached).

Figure 1. Master–slave manipulator, with French roboticist Jean Vertut and author Thomas B. Sheridan. (Photo courtesy of the author.)

In the medical arena, surgical telerobots, such as the DaVinci system (first approved by the Food and Drug Administration in 2000), are now permitting greater precision (scaling down and dejittering) of the surgeon's hand motions for minimally invasive surgery. Physically handicapped persons are now experiencing improved arm manipulation and walking prostheses and orthoses (Kazerooni, 2008). Human factors research is needed to improve the fitting of such devices to patients as a function of their particular neuromuscular abilities and deficits.

Automated Highway and Rail Vehicles, Commercial Aircraft

The earlier DARPA "Grand Challenge" contests of autonomous vehicles in 2004, 2005, and 2007 proved that vehicles guided by artificial intelligence were feasible (see "DARPA Grand Challenge" in Wikipedia). As is well known, recently Google has produced a self-driven car, demonstrated successfully on California freeways (and experienced by this author). However, beyond feasibility demonstrations, it is fallacious to assume a human driver will stay alert and be ready to take over control within a few seconds should the automation fail.

Meanwhile, many other automobile manufacturers have been developing technology to augment

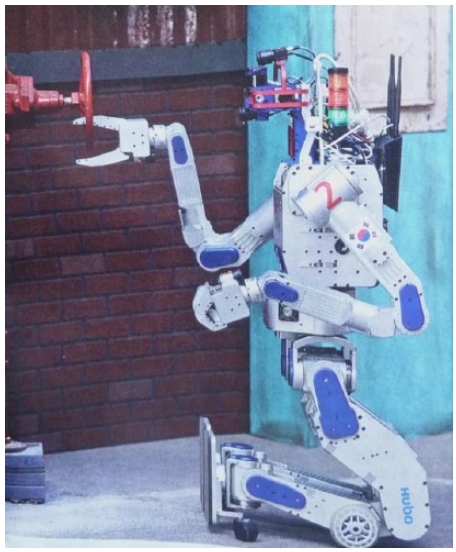

Figure 2. KAIST robot opening a valve. From "Team KAIST. DARPA Robotics Challenge," by DARPA, 2015 (http://www.theroboticschallenge.org/finalist/kaist). In the public domain.

the human driver, such as radar-augmented cruise control, run-off-the-road alarms, and vehicle-to-vehicle communication for preventing intersection collisions. It is becoming clear that many complex traffic situations are exceedingly difficult for computer vision and artificial intelligence to "understand" and that many accidents are avoided by social interaction between drivers, such as mutual eye contact, hand signals, and so on (Gao, Lee, & Zhang, 2006; Lee & See, 2004; Schoettle & Sivak, 2015; Seppelt & Lee, 2007). Understanding the social aspects of driving in traffic, as well as the degree to which cars can be safely automated, demands much further research.

Urban planners have long dreamed of rail-based fully automated transit systems, but they are currently limited to airports or airport-to-city-center systems.

I include commercial aircraft here because they are telerobots insofar as the pilots mostly fly by exerting supervisory control using the flight management system responsible for control, guidance, and navigation. Sheridan (2015) pointed out that these common aviation concepts correlate well with Rasmussen's (1986) skill, rule, and knowledge behavior components. Aircraft pitch, roll, and yaw are accomplished by closed-loop control akin to subconscious human perceptual motor *skills*, for example, steering a car on the roadway. Guidance is the integration of speed, altitude, and heading to maintain a proper trajectory, for example, following traffic *rules* to stop at traffic lights, get in the proper lanes, and make correct turns. Navigation to get to an airport destination is largely a *knowledge*-based activity that draws on map memory and current weather and traffic models, often involving rethinking the task to avoid bad weather and other aircraft and modifying the schedule, much like what humans do in planning a walk or a drive to a destination.

The frontier of aviation is currently the adoption of GPS navigation (replacing radar), guidance based on improved weather modeling and digital communication with the ground and nearby aircraft (mostly replacing voice and vision), and adaptive thrust and airfoil control. According to NASA (Croft, 2015), technology exists to remove the second pilot from commercial aircraft, using ground-base monitoring over secure communication to replace the copilot; passenger acceptance is a different and more challenging question.

Human factors research needs to include human-in-the loop simulations, especially for off-nominal situations (the Federal Aviation Administration is doing too few of these), and evaluation of digital as compared with voice communication.

Human–Robot Social Interaction

MIT's Kismet is an expressive robot head with "social intelligence," according to researcher reports (Adolphs, 2005; Breazeal, 2000). Using computer processing of the face and voice of another person, Kismet makes appropriate gestures in return. One can debate whether this technology is truly social intelligence, but it surely poses interesting philosophical questions. Evidence suggests that such devices are effective at eliciting "normal" social interaction with young children. However, one can wonder whether such devices inhibit healthy imagination (evidenced by children playing with passive dolls) rather than enhance it (Turkle, 2011).

A number of toys and therapeutic animal or human figures that are coming on the market embody computer-based speech, speech recognition, and decision-making software. For example, Mattel has developed a new Barbie doll with an extensive speech and language recognition vocabulary that is linked via the Internet to the

company server (Vlahos, 2015). The doll is designed to carry on an extensive conversation with young girls or boys in areas of their interest.

Knox, Breazeal, and Stone (2013) present a case study of applying a framework for learning from human feedback to an interactive robot. They claim this application as a first demonstration of the ability to train multiple behaviors in robot learning from free-form human-generated feedback without any further guidance or evaluative feedback.

Getting hospital patients and especially the elderly to trust and not be alienated by robots in such functions as exercise coaching and delivery of food trays is a research need that is natural for human factors professionals. Demonstrations by Fasola and Matarić (2013) and Feil-Seifer and Matarić (2011) are exemplary. However, Knefel (2015) questions whether one ever should fully trust a robot.

Use of robot interaction in education is not a new idea. For example, the LOGO language of Papert (1980) used robotic "turtles" as a means for children to learn elementary programming. That effort evolved to the current commercial LEGO Mindstorms product for children. There are human factors challenges for a person teaching a robot and for a robot teaching a person. Previous experience suggests that ideally both occur simultaneously.

HUMAN FACTORS RESEARCH NEEDS ON CROSS-CUTTING "HARD PROBLEMS" OF HRI

Task Dynamic Analysis

An important component of the human factors tool kit is task analysis. A somewhat different line of human factors research is allocation of tasks between humans and automation. The famous Fitts (1951) list for what each of "man" and machine can best do is well out of date and has yet to be revised in a definitive way. Miniature sensors, artificial intelligence (AI), and high-bandwidth communication have clearly advanced machine capabilities. If one thinks that ergonomics is old-style human factors, consider designing a robot to move elderly and handicapped people gently in and out of bed or to the toilet. Many human caretakers do this job now and injure their backs in the process. The challenge of task planning and simulation in time, space, force, energy, and cost—possibly with virtual-reality envisioning aids—has never been greater. There is also the issue of whether general-purpose robots in humanoid form make sense; experience suggests that the physical form of a robot is best determined by task context. How to analyze HRI tasks so as to predict the best physical form is itself a challenge.

Teaching a Robot and Avoiding Unintended Consequences

A human can give geometric instructions by moving the robot hand, but specifying how to move, when to move, what to avoid, and so on requires symbolic rather than analogic language. Rapid advances in computer-based speech understanding (e.g., Apple's SIRI) promises ease in commanding robots. But there is great possibility for unintended consequences. One answer may be for human supervisors to use real-time virtual-reality simulation to observe what the spoken commands will cause the robot to do—before giving the "go" signal to the robot. This approach in effect would be an extension of predictor displays that continually update models of the process being controlled to "look ahead" by model extrapolation (Sheridan, 1992, pp. 214–219).

Interfacing Mutual "Mental" Models to Avoid Working at Cross-Purposes

The notion of both humans and robots having internal (mental) models of one another has long been suggested (e.g., Sheridan & Verplank, 1978). Computer vision can now watch people's actions, store data as stick-figure models, and do Bayesian analysis and prediction. Eliciting mental models from humans of what robots can or should do, and combining that knowledge with the computer's model for purposes of planning and conflict avoidance, remains an HRI challenge. Experience in AI (visual pattern recognition, language translation) has suggested that matching the first 90% of human capability may be relatively easy, but the last 10% is extremely difficult because of the vast wealth of human worldly experience.

Role of Robots in Education

Learning from books and canned lectures is possible but can be difficult and boring, and it

will not even work for children who do not read or adults with cognitive disabilities. Interacting with a live human teacher or colearner almost always enhances the learning process. Ever since Papert's early experiments on children teaching a mechanical "turtle" cited earlier, the robot has figured in considering the future of education: to add fun, to serve as an avatar to be taught or to speak, to demonstrate a physical relationship (as in physics), or to react to student responses (with criticism or reinforcement). Robot learning from other robots as well as humans is an active workshop topic (see IEEE Robotics and Automation Society, 2015). Understanding how people of different ages and abilities best learn from robots remains an important challenge that human factors should contribute to.

Lifestyle, Fears, and Human Values

The Czech playwright Karel Capek is generally credited with the first use of the term *robot* in his play *Rossum's Universal Robots* in 1920. Originally his sci-fi/horror scenario caused amusement but seemed unrealistic. Today we see new horror films featuring robot takeover of jobs and encroachment on personal dignity. The media have become absorbed by robots for both their positive and negative implications for society. Modern film versions include *Star Wars, Wall-E, Ex-Machina*, and many more.

Obviously there are trade-offs that need serious discussion: robots providing jobs versus taking them away, robots as useful assistants enhancing human sense of self-worth versus diminishing human sense of self-worth, robots improving human security versus becoming spies (e.g., miniature UAVs), saboteurs, and killers. I believe human factors scientists are more attuned to the realities of living and working with robots than is the general public. Therefore human factors professionals have an obligation to participate in discussions and policy planning on these issues, including public education. If we could automate everything, what would we want to be automated and what not automated?

CONCLUSIONS

Research and design in HRI demands much greater participation by the human factors community than has occurred in the past, except for some contexts, such as commercial aviation and military systems, where human factors professionals have long participated. Current technology for "self-driving" cars and drones poses huge challenges for safety and acceptability.

With regard to the Task Dynamic Analysis discussion earlier, human factors professionals definitely need to become more sophisticated in understanding dynamics and control, if only at a basic level. We need to revisit the discussions of where humans best fit into systems as compared with AI and computer control. However, shortcomings of AI in understanding context need to be appreciated by system designers.

Teaching (instructing, programming) a robot is a language problem. The diversity and burgeoning aspects of HRI reviewed earlier suggest great opportunities for human factors involvement in researching and designing symbolic teaching.

With regard to mental models, that is, what operators are thinking, what they know, whether they misunderstand, and so on, research is critical as systems get more complex and the stakes get higher. Modern control techniques depend on built-in models of what is going on in the environment that are continually updated, much as what humans seem to do. Research in mental models by cognitive scientists (e.g., Johnson-Laird, 1983) is not new, but human factors has now employed mental constructs, like situation awareness and trust, that imply active mental models. I believe practical means to elicit operator mental models (both in real time and offline) and to compare these models with what computers assess of situations will have safety and efficiency benefits in human–robot systems.

Education (and training) has always been part of human factors, and computers have fit into training systems for many years. Use of robots (computers that have bodies, that can move about, that can show affect, and that can act like people) seems a natural extension of using passive computers in education.

Research in the areas relating to lifestyle, fears, and human values is probably the most important challenge for HRI. If a job can be more efficiently done by a robot, should that job always be automated? How can robots be made to work as active, intelligent task helpers in industrial tasks or in caring for the sick or elderly?

In national security contexts, should robots ever be authorized to "use their own judgment" in deciding whether to kill someone or destroy property, or must humans always be in the decision loop? Many writers are posing these big questions, but research is lacking. Can human factors methods and insights be extended to help answer such questions, or do we have nothing to contribute?

KEY POINTS

- Major human factors research challenges include (a) task analysis that includes dynamics, economics, and other factors; (b) teaching the robot and avoidance of unintended consequences; (c) considering how both human and robot have mutual models of each other; (d) use of robots in education; (e) coping with user culture, fears, and other value considerations.
- To date, except for aviation, the human factors community has contributed a very small fraction of the human–robotics papers in the literature.
- Essentially, all robots for the foreseeable future will be controlled by humans, either as teleoperators steered by continuous manual movement or as telerobots intermittently monitored and reprogrammed by human supervisors.
- Human–robot interaction (HRI) is a rapidly expanding field with a great need for human factors involvement in research and design, especially as robots are challenged to undertake more sophisticated tasks. In any case, the first 90% of replacing humans with robots is much easier than the last 10%.
- Whereas the human race is changing very slowly, computers and robots are evolving at a very rapid pace. Therefore, specific conclusions about HRI are likely to become invalid in a short time. The motivation of the HRI community seems more focused on building and demonstrating what works and provoking new ideas than in providing detailed and validated scientific conclusions.

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