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Human–Robot Interaction: A Survey

Michael A. Goodrich[1] and Alan C. Schultz[2]

[1] Brigham Young University, Provo, UT 84602, USA, mike@cs.byu.edu
[2] US Naval Research Laboratory, Washington, DC 20375, USA,
   schultz@aic.nrl.navy.mil

Abstract

Human–Robot Interaction (HRI) has recently received considerable
attention in the academic community, in labs, in technology compa-
nies, and through the media. Because of this attention, it is desirable
to present a survey of HRI to serve as a tutorial to people outside
the field and to promote discussion of a unified vision of HRI within
the field. The goal of this review is to present a unified treatment of
HRI-related problems, to identify key themes, and discuss challenge
problems that are likely to shape the field in the near future. Although
the review follows a survey structure, the goal of presenting a coher-
ent "story" of HRI means that there are necessarily some well-written,
intriguing, and influential papers that are not referenced. Instead of
trying to survey every paper, we describe the HRI story from multiple
perspectives with an eye toward identifying themes that cross appli-
cations. The survey attempts to include papers that represent a fair
cross section of the universities, government efforts, industry labs, and
countries that contribute to HRI, and a cross section of the disciplines
that contribute to the field, such as human, factors, robotics, cognitive
psychology, and design.

1

Introduction

Human–Robot Interaction (HRI) is a field of study dedicated to understanding, designing, and evaluating robotic systems for use by or with humans. Interaction, by definition, requires communication between robots and humans. Communication between a human and a robot may take several forms, but these forms are largely influenced by whether the human and the robot are in close proximity to each other or not. Thus, communication and, therefore, interaction can be separated into two general categories:

- Remote interaction — The human and the robot are not co-located and are separated spatially or even temporally (for example, the Mars Rovers are separated from earth both in space and time).
- Proximate interaction — The humans and the robots are co-located (for example, service robots may be in the same room as humans).

Within these general categories, it is useful to distinguish between applications that require mobility, physical manipulation, or social interaction. Remote interaction with mobile robots is often referred

to as teleoperation or supervisory control, and remote interaction with a physical manipulator is often referred to as telemanipulation. Proximate interaction with mobile robots may take the form of a robot assistant, and proximate interaction may include a physical interaction. Social interaction includes social, emotive, and cognitive aspects of interaction. In social interaction, the humans and robots interact as peers or companions. Importantly, social interactions with robots appear to be proximate rather than remote. Because the volume of work in social interactions is vast, we present only a brief survey; a more complete survey of this important area is left to future work.

In this review, we present a survey of modern HRI. We begin by presenting key developments in HRI-related fields with the goal of identifying critical technological and scientific developments that have made it possible for HRI to develop as a field of its own. We argue that HRI is not simply a reframing and reformulation of previous work, but rather a new field of scientific study. To support this argument, we identify seminal events that signal the emergence of HRI as a field. Although we adopt a designer-centered framing of the review, work in the field requires strong interdisciplinary blends from various scientific and engineering fields.

After surveying key aspects in the emergence of HRI as a field, we define the HRI problem with an emphasis on those factors of interaction that a designer can shape. We then proceed to describe the application areas that drive much of modern HRI. Many of these problems are extremely challenging and have strong societal implications. We group application areas into the previously mentioned two general categories, remote and proximate interactions, and identify important, influential, or thought-provoking work within these two categories. We follow this by describing common solution concepts and barrier problems that cross application domains and interaction types. We then briefly identify related work from other fields involving humans and machines interacting, and summarize the review.

2

Early History of Robotics and Human–Machine-Interaction

In this section, we briefly survey events and work that have made modern HRI possible. Clearly, the development of robots was the essential first step. Although robot technology was primarily developed in the mid and late 20th century, it is important to note that the notion of robot-like behavior and its implications for humans have been around for centuries in religion, mythology, philosophy, and fiction. The word "robot" originates from the Czechoslovakian word *robota* which means work [309]. "Robot" appears to have first been used in Karel Chapek's 1920's play *Rossum's Universal Robots*, though this was by no means the earliest example of a human-like machine. Indeed, Leonardo da Vinci sketched a mechanical man around 1495, which has been evaluated for feasibility in modern times [250]. Pre-dating da Vinci's humanoid robot are *automata* and mechanical creatures from ancient Egypt, Greece, and China. The Iliad refers to golden maids that behave like real people [125]. The idea of *golem*, an "artificial being of Hebrew folklore endowed with life" has been around for centuries [309] and was discussed by Wiener in one of his books [315]. Ancient Chinese legends and compilations mention robot-like creations, such as the story from the West Zhou Dynasty (1066BC–771BC) that

describes how the craftsman Yanshi presented a humanoid. The creation looked and moved so much like a human that, when it winked at the concubines, it was necessary to dismantle it to prove that it was an artificial creation [328]. Similar robotic devices, such as a wooden ox and floating horse, were believed to have been invented by the Chinese strategist Zhuge Liang [316], and a famous Chinese carpenter was reported to have created a wooden/bamboo magpie that could stay aloft for up to three days [297]. More recently, robotic-like automata, including Vaucanson's duck, have been created [243]. Mechanical-like birds were present in the 1933 poem *Byzantium* by W. B. Yeats [326], and robots have had a large presence in science fiction literature, most notably Azimov's works [12]. Indeed, Asimov's *Laws of Robotics* appear to be the first designer guidelines for HRI.

Early robot implementations were remotely operated devices with no or minimal autonomy (Figure 2.1). In 1898, Nicola Tesla demonstrated a radio-controlled boat, which he described as incorporating "a borrowed mind." In fact, Tesla controlled the boat remotely. His invention, which he generalized to many different types of vehicles, was described in patent 613,809, "Method and Apparatus for Controlling Mechanism of Moving Vessels." Tesla hypothesized, "...you see there
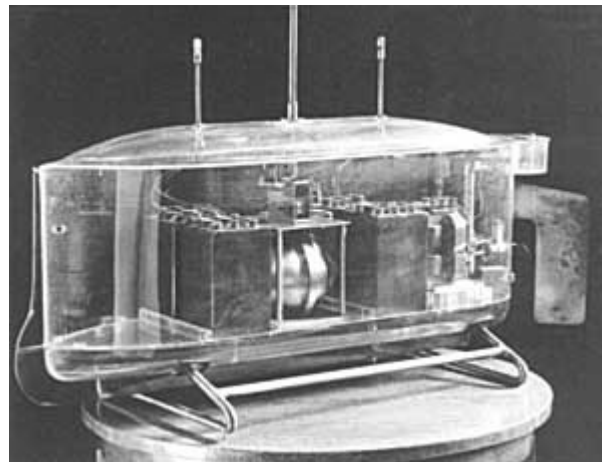

Fig. 2.1 Tesla's boat [287].

the first of a race of robots, mechanical men which will do the laborious work of the human race." He even envisioned one or more operators simultaneously directing 50 or 100 vehicles.

Other examples include: The Naval Research Laboratory's "Electric Dog" robot from 1923, attempts to remotely pilot bombers during World War II, the creation of remotely piloted vehicles, and mechanical creatures designed to give the appearance of life. As technology evolved, the capabilities of remotely operated robots have grown (see [95] for a brief history). This is perhaps nowhere more evident then in the very successful application of unmanned underwater vehicles that have been used to explore the ocean's surface to find lost ships, explore underwater life, assist in underwater construction, and study geothermal activity [313].

Complementing the advances in robot mechanics, research in artificial intelligence has attempted to develop fully autonomous robots. The most commonly cited example of an early autonomous robot was Shakey, which was capable of navigating through a block world under carefully controlled lighting conditions at the glacially slow speed of approximately 2 meters per hour [209]. Many agree that these early works laid a foundation for much that goes on in hybrid control architectures today [196, 223].

A breakthrough in autonomous robot technology occurred in the mid 1980s with work in behavior-based robotics [10, 38]. Indeed, it could be argued that this work is a foundation for many current robotic applications. Behavior-based robotics breaks with the monolithic sense-plan-act loop of a centralized system, and instead uses distributed sense-response loops to generate appropriate responses to external stimuli. The combination of these distributed responses produces "emergent" behavior that can produce very sophisticated responses that are robust to changes in the environment. A second important breakthrough for autonomy as it applies to HRI is the emergence of hybrid architectures; these architectures simultaneously allow sophisticated reactive behaviors that provide fundamental robot capabilities along with the high-level cognitive reasoning required for complex and enduring interactions with humans. Robot behaviors initially focused on mobility, but more recent contributions seek to develop lifelike anthro-

pomorphic behaviors [323], acceptable behaviors of household robots [158], and desirable behaviors for robots that follow, pass, or approach humans [105, 220, 307].

The development of robust robot platforms and communications technologies for extreme environments has been accomplished by NASA and other international space agencies. Space agencies have had several high profile robotic projects, designed with an eye toward safely exploring remote planets and moons. Examples include early successes of the Soviet Lunokhods [95] and NASA's more recent success of exploring the surface of Mars [174, 317]. Importantly, many of the failures have been the result of software problems rather than mechanical failures. Complementing NASA's fielded robots have been several robots developed and evaluated on earth [17]. Robonaut is a well-known example of successful teleoperation of a humanoid robot [9], and this work is being extended at a rapid pace to include autonomous movement and reasoning. Autonomous robots that have the anthropomorphic dimensions, mimic human-like behaviors, and include human-like reasoning are known as humanoid robots; work in this area has been ongoing for over a decade and is rapidly expanding [9, 23, 31, 37, 153, 273, 285].

Emerging from the early work in robotics, human factors experts have given considerable attention to two paradigms for human–robot interaction: teleoperation and supervisory control. At the teleoperation extreme, a human remotely controls a mobile robot or robotic arm. With supervisory control, a human supervises the behavior of an autonomous system and intervenes as necessary. Early work was usually performed by people who were interested not only in robotics but also factory automation, aviation, and intelligent vehicles. Work in these areas is typified by Sheridan's seminal contributions [267, 268], and other significant contributions from human factors researchers [193, 314].

Every robot application appears to have some form of interaction, even those that might be considered "fully autonomous." For a teleoperated robot, the type of interaction is obvious. For a fully autonomous robot, the interaction may consist of high-level supervision and direction of the robot, with the human providing goals and with the robot maintaining knowledge about the world, the task and its constraints.

In addition, the interactions may be through observation of the environment and implicit communications by, for example, the robot responding to what its human peer is doing. Taking a very broad and general view of HRI, one might consider that it includes developing algorithms, programming, testing, refining, fielding, and maintaining the robots. In this case, interaction consists primarily in discovering and diagnosing problems, solving these problems, and then reprogramming (or rewiring) the robot. The difference between this type of "programming-based" interaction and modern HRI is that the field currently emphasizes efficient and dynamic interactions rather than just infrequent interactions. However, some researchers are addressing programming-based of interaction by exploring efficient programming paradigms to support robot development [128, 327].

3

Emergence of HRI as a Field

Although there is much work that can be considered HRI, the multi-disciplinary field started to emerge in the mid 1990s and early years of 2000. Key numerous events occurred in this time frame, with the main catalyst being a multi-disciplinary approach; researchers from robotics, cognitive science, human factors, natural language, psychology, and human–computer interaction started to come together at these events specifically recognizing the importance of working together.

The earliest scientific meeting, which started in 1992 and continues annually, is the IEEE International Symposium on Robot & Human Interactive Communication (RoMan). Although recently this conference has attracted a more multi-disciplinary research community, historically it has been heavily dominated by the robotics discipline. In 2000, the IEEE/Robotics Society of Japan created the International Conference on Humanoid Robots which highlights anthropomorphic robots and robotic behaviors.

From the late 1990s until recently, there have been many workshops and conference tracks dedicated to HRI, including ones associated with the Association for the Advancement of Artificial Intelligence's (AAAI) Symposia Series, IEEE International Conference on

211

Robotics and Automation (ICRA), Robotics Systems and Sciences, the IEEE/Robotics Society of Japan International Conference on Intelligent Robot and Systems, among others, and the annual meeting of the Human Factors and Ergonomics Society.

In 2001, the US National Science Foundation and Defense Advanced Research Projects Agency sponsored a workshop on human–robot interaction, organized by Dr Robin Murphy and Dr Erica Rogers [46]. The purpose of this workshop was to bring together a highly multidisciplinary group of researchers working in areas close to HRI, and to help identify the issues and challenges in HRI research. Although much research had been done prior to this event, some consider it to be seminal in the emergence of the field as its own discipline. A second NSF workshop was held in 2006 [181].

In July 2004, IEEE-RAS and the International Foundation of Robotics Research (IFRR) sponsored a summer school on "Human–Robot Interaction." This event brought together six experts from the field of HRI and approximately 30 PhD students for a week in Volterra Italy for four intensive days of lectures and events. A similar event that has been held annually since 2004 is the Rescue Robotics Camp (see, for example, [239, 240]). About the same time, a series of special issues dedicated to HRI began to appear in journals [5, 157, 171, 201, 261].

In 2005, the US National Research Council sponsored a workshop entitled "Interfaces for Ground and Air Military Robots" [64]. The workshop discussed emerging interface and autonomy themes that could be used across multiple scales to support primarily remote interaction of humans and robots.

The Japan Association for the 2005 World Exposition conducted a Robot Project at EXPO 2005 that featured a wide range of robots [6]. Guide, cleaning, service, and assistive robots were among the many robots that were featured.

Starting in 2006, the ACM International Conference on Human–Robot Interaction was created to specifically address the multidisciplinary aspects of HRI research. Reflecting this multidisciplinary nature, the 2007 conference was co-sponsored by the ACM Special Interest Group on Computer Human Interaction, the ACM Special

Interest Group on Artificial Intelligence, and the IEEE Robotics and Automation Society (RAS), with co-technical sponsorship from AAAI, the Human Factors and Ergonomics Society, and the IEEE Systems, Man, and Cybernetics Society. Associated with the HRI conference is a NSF-funded student workshop. Other conferences have had a strong interest in HRI including the following: the Humanoid Robotics workshops; the IEEE International Workshop on Safety, Security, and Rescue Robotics; and the Performance Metrics for Intelligent Systems workshop.

In 2006, the European Land-Robot Trial (ELROB) was created to "provide an overview of the European state-of-the-art in the field of [Unmanned Ground Vehicles]" [87]. Such systems frequently included robust user interfaces intended for field conditions in challenging environments, such as those faced in military and first responder domains.

Another big influence in the emergence of HRI has been competitions. The two with the greatest impact have been (a) the AAAI Robotics Competition and Exhibition and (b) the Robocup Search and Rescue competition. The Sixth AAAI Robot Competition in 1997 had the first competition specifically designed for HRI research called "Hors d'Oeuvres Anyone?" The goal of the competition was for a robot to serve snacks to attendees of the conference during the conference reception. This event was repeated in 1998. Starting in 1999, a new grand challenge event was introduced. For this competition, a team's robot had to be dropped off at the front door of the conference venue and, through interaction with people, find its way to the registration desk, register for the conference, and then find its way at the correct time to a place where it was to give a presentation. This task was designed to be hard enough to take many years to accomplish, helping to drive research (see, for example, [276]). In recent years this conference held several general human-interaction events.

In some cases, an application domain has helped to draw the field together. Three very influential areas are robot-assisted search and rescue, assistive robots, and space exploration. Literature from each of these domains is addressed further in a subsequent section. Robot-assisted search and rescue has been a domain in which the

robotics field has worked directly with the end users which, in this case, consists of specially trained rescue personnel. The typical search and rescue situation involves using a small robot to enter into a potentially dangerous rubble pile to search for victims of a building collapse. The robots are typically equipped with a video camera and possibly chemical and temperature sensors, and may sometimes be equipped with a manipulator with which they can alter the environment. The goal is to quickly survey an area that would otherwise be unsafe for a human searcher to enter, and gather information about victim location and structural stability. Because of the inherently unstructured nature of search and rescue domains, the interactions between the human and the robot are very rich. Consequently, many HRI issues are addressed in the problem, and several ongoing competitions are held to encourage robotics researchers to participate [159, 199, 325].

Assistive robot systems seek to provide physical, mental, or social support to persons who could benefit from it such as the elderly or disabled. Assistive robotics is important to HRI because it emphasizes proximate interaction with potentially disabled persons. HRI challenges from this domain include providing safe physical contact or moving within very close proximity. The challenges also include supporting effective social interactions through cognitive and emotive computing, and through natural interactions such as gesture and speech. Although sometimes referred to by names other than robots, the types of robots/machines used in assistive applications vary widely in their physical appearance, and include wheelchairs, mobile robots with manipulators, animal-like robots, and humanoids [90, 206, 246, 299]. Because of the close proximity and sometimes long-term interactions, appropriate HRI in assistive robotics may be sensitive to cultural influences [152, 270].

Space robotics has also been an important domain for HRI because of the challenges that arise under such extreme operating conditions. These challenges include operating a remote robot when the time lag can be a significant factor, or interacting in close proximity such as when a robot assistant helps an astronaut in exploring the surface of a planetary body. A typical anticipated situation is a geological

study that involves prolonged work on the surface of a planetary body, possibly using specialized sensors such as ground-penetrating radar and specialized manipulators such as a drill and hammer [84]. Information gathered by the robot needs to be returned either (a) to an astronaut who is co-located with the robot or (b) to a ground-bases science team who then form real-time hypotheses that are used to modify the behavior of the robot.

4

What Defines an HRI Problem?

The HRI problem is to *understand and shape the interactions between one or more humans and one or more robots*. Interactions between humans and robots are inherently present in all of robotics, even for so called autonomous robots — after all, robots are still used by and are doing work for humans. As a result, evaluating the capabilities of humans and robots, and designing the technologies and training that produce desirable interactions are essential components of HRI. Such work is inherently interdisciplinary in nature, requiring contributions from cognitive science, linguistics, and psychology; from engineering, mathematics, and computer science; and from human factors engineering and design.

Although analysis of anticipated and existing interaction patterns is essential, it is helpful to adopt the designer's perspective by breaking the HRI problem into its constituent parts. In essence, a designer can affect five attributes that affect the interactions between humans and robots:

- Level and behavior of autonomy,
- Nature of information exchange,
- Structure of the team,

- Adaptation, learning, and training of people and the robot, and
- Shape of the task.

Interaction, *the process of working together to accomplish a goal*, emerges from the confluence of these factors. The designer attempts to understand and shape the interaction itself, with the objective of making the exchange between humans and robots beneficial in some sense. We now discuss each of these attributes in detail, including references from the literature.

4.1   Autonomy

Designing autonomy consists of mapping inputs from the environment into actuator movements, representational schemas, or speech acts. There are numerous formal definitions of autonomy and intelligence in the literature [7, 20, 119, 184, 256], many of which arise in discussions of adjustable or dynamic autonomy [30]. One operational characterization of autonomy that applies to mobile robots is the amount of time that a robot can be neglected, or the *neglect tolerance* of the robot [68]. A system with a high level of autonomy is one that can be neglected for a long period of time without interaction. However, this notion of autonomy does not encompass Turing-type notions of intelligence that might be more applicable to representational or speech-act aspects of autonomy.

Autonomy is not an end in itself in the field of HRI, but rather a means to supporting productive interaction. Indeed, autonomy is only useful insofar as it supports beneficial interaction between a human and a robot. Consequently, the physical embodiment and type of autonomy varies dramatically across robot platforms; see Figure 4.1, which shows a cross section of the very many different types of physical robots.

Perhaps the most strongly human-centered application of the concept of autonomy is in the notion of *level of autonomy (LOA)*. Levels of autonomy describe to what degree the robot can act on its own accord. Although many descriptions of LOA have been seen in the literature, the most widely cited description is by Tom Sheridan [269]. In Sheridan's scale, there is a continuum from the entity being completely con-

Fig. 4.1 Representative types of robots. In clockwise order beginning in the upper left: RepileeQ2 — an extremely sophisticated humanoid [136]; Robota — humanoid robots as "educational toys" [21]; SonyAIBO — a popular robot dog ; (below the AIBO) A sophisticated unmanned underwater vehicle [176]; Shakey — one of the first modern robots, courtesy of SRI International, Menlo Park, CA [279]; Kismet — an anthropomorphic robot with exaggerated emotion [65]; Raven — a mini-UAV used by the US military [186]; iCAT — an emotive robot [REF]; iRobot® PackBot® — a robust ground robot used in military applications [135]. (All images used with permission.)

trolled by a human (i.e., teleoperated), through the entity being completely autonomous and not requiring input or approval of its actions from a human before taking actions:

1. Computer offers no assistance; human does it all.
2. Computer offers a complete set of action alternatives.
3. Computer narrows the selection down to a few choices.
4. Computer suggests a single action.
5. Computer executes that action if human approves.
6. Computer allows the human limited time to veto before automatic execution.
7. Computer executes automatically then necessarily informs the human.
8. Computer informs human after automatic execution only if human asks.

9. Computer informs human after automatic execution only if it decides too.
10. Computer decides everything and acts autonomously, ignoring the human.

Variations of this scale have been developed and used by various authors [144, 222]. Importantly, Miller and Parasuraman have noted that such scales may not be applicable to an entire problem domain but are rather most useful when applied to each subtask within a problem domain [188]. The authors further suggest that previous scales actually represent an average over all tasks.

While such (average) scales are appropriate to describe how autonomous a robot is, from a human–robot interaction point of view, a complementary way to consider autonomy is by describing to what level the human and robot interact and the degree to which each is capable of autonomy. The scale presented in Figure 4.2 gives an emphasis to mixed-initiative interaction, which has been defined as a "flexible interaction strategy in which each agent (human and [robot]) contributes what it is best suited at the most appropriate time" [122]. Various and different HRI issues arise along this scale. On the direct control side, the issues tend toward making a user interface that reduces the cognitive load of the operator. On the other extreme of peer-to-peer collaboration, issues arise in how to create robots with the appropriate cognitive skills to interact naturally or efficiently with a human.

Note that in order for the robot to achieve peer-to-peer collaboration, it must indeed be able to flexibly exhibit "full autonomy" at appropriate times. Moreover, it may need to support social interactions.
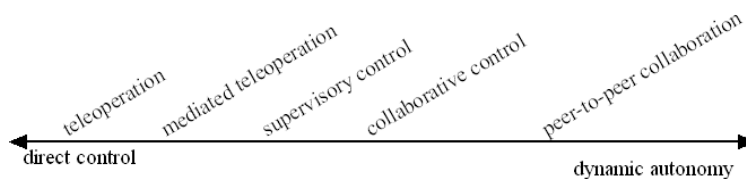

Fig. 4.2 Levels of autonomy with emphasis on human interaction.

As a result, peer-to-peer collaboration may be considered more difficult to achieve than full autonomy.

Autonomy is implemented using techniques from control theory, artificial intelligence, signal processing, cognitive science, and linguistics. A common autonomy approach is sometimes referred to as the *sense-plan-act* model of decision-making [196]. This model has been a target of criticism [39] and sometimes rightfully so, but much of the criticism may be a function of the early capacities of robots such as Shakey [209] rather than failings of the model *per se*. This model is typified by artificial intelligence techniques, such as logics and planning algorithms [253]. The model can also incorporate control theoretic concepts, which have been used very successfully in aviation, aeronautics, missile control, and etc. (see, for example, [175]).

In the mid 1980s, Brooks, Arkin, and others revolutionized the field of robotics by introducing a new autonomy paradigm that came to be known as *behavior-based robotics*. In this paradigm, behavior is generated from a set of carefully designed autonomy modules that are then integrated to create an emergent system [10, 38, 40]. These modules generate reactive behaviors that map sensors directly to actions, sometimes with no intervening internal representations. This model for behavior generation was accompanied by hardware development that allowed autonomy modules to be implemented in the small form factors required for many robotics applications.

Today, many researchers build sense-think-act models on top of a behavior-based substrate to create *hybrid* architectures [196]. In these systems, the low-level reactivity is separated from higher level reasoning about plans and goals [28]. Some have developed mathematics and frameworks that can be viewed as formalizations of hybrid architectures and which are referred to as theories of intelligent control [7, 255]. Interestingly, some of the most challenging problems in developing (hybrid) behaviors is in producing natural and robust activity for a humanoid robot [194, 273, 323].

Complementing the advancement of robotic control algorithms has been the advancement of sensors, sensor-processing, and reasoning algorithms. This is best represented by the success of the field of *probabilistic robotics*, typified by probabilistic algorithms for localization

and mapping [161, 289]. It is no overstatement to say that these algorithms, which frequently exploit data from laser and other range finder devices, have allowed autonomy to become truly useful for mobile robots [290], especially those that require remote interaction through periods of autonomous behavior and autonomous path planning [42, 276, 284, 291, 293]. Although probabilistic algorithms can be computationally expensive, the memory capacity, computational speed, and form factor of modern computers have allowed these algorithms to be deployable.

The areas of representing knowledge and performing reasoning, especially in team contexts, have also grown. Example developments include the emergence of belief-desire-intention architectures [321], joint intention theory [60], affect-based computing [31, 223, 229], and temporal logics.

4.2 Information Exchange

Autonomy is only one of the components required to make an interaction beneficial. A second component is the manner in which information is exchanged between the human and the robot (Figure 4.3). Measures of the efficiency of an interaction include the *interaction time* required for intent and/or instructions to be communicated to the robot [68], the *cognitive* or *mental workload* of an interaction [268], the amount of *situation awareness* produced by the interaction [88] (or reduced because of interruptions from the robot), and the amount of shared understanding or common ground between humans and robots [143, 160].

There are two primary dimensions that determine the way information is exchanged between a human and a robot: the *communications medium* and the *format of the communications*. The primary media are delineated by three of the five senses: seeing, hearing, and touch. These media are manifested in HRI as follows:

- visual displays, typically presented as graphical user interfaces or augmented reality interfaces [15, 145, 154, 208],
- gestures, including hand and facial movements and by movement-based signaling of intent [31, 73, 247, 305],

Fig. 4.3 Types of human–robot interaction. Counterclockwise from top left: haptic robot interaction from Georgia Tech [102], a "physical icon" for flying a UAV from Brigham Young University, peer-to-peer interaction with the robot Kaspar from the University of Hertfordshire [298], teleoperation of NASA's Robonaut [205], a PDA-based interface for flying a UAV from Brigham Young University, gesture- and speech-based interaction with MIT's Leonardo [189], a touchscreen interaction with a Cogniron robot [169], and (center) physical interaction with the RI-MAN robot [24]. (All images used with permission.)

- speech and natural language, which include both auditory speech and text-based responses, and which frequently emphasize dialog and mixed-initiative interaction [126, 227],
- non-speech audio, frequently used in alerting [78], and
- physical interaction and haptics, frequently used remotely in augmented reality or in teleoperation to invoke a sense of *presence* especially in telemanipulation tasks [10, 282], and also frequently used proximately to promote emotional, social, and assistive exchanges [56, 124, 172, 272].

Recently, attention has focused on building multimodal interfaces [226], partly motivated by a quest to reduce workload in accordance to Wickens' multiple resource theory [314] and partly motivated by a desire to make interactions more natural and easier to learn [248, 254, 281].

The *format* of the information exchange varies widely across domains. Speech- and natural language-based exchanges can be scripted and based on a formal language, can attempt to support full natural language, or can restrict natural language to a subset of language and a restricted domain (see, for example, [52, 120, 251, 275, 276]). Importantly, speech-based exchanges must not only address the content of information exchanged, but also the rules of such exchange a lá the Gricean maxims [118], which ask to what extent the speech is truthful, relevant, clear, and informative. Haptic information presentation can include giving warnings through vibrations, promoting the feeling of telepresence, supporting spatial awareness through haptic vests, and communicating specific pieces of information through haptic icons (see, for example, [53, 164, 235]). Audio information presentation can include auditory alerts, speech-based information exchange, and 3D awareness (see, for example, [285]). Presenting social information can include attentional cueing, gestures, sharing physical space, imitation, sounds, facial expression, speech and natural language [22, 35, 36, 83, 94, 203, 149, 260]. Finally, graphical user interfaces present information in ways that include ecological displays, immersive virtual reality, and traditional windows-type interactions (see, for example, [9, 15, 185, 208]).

4.3   Teams

HRI problems are not restricted to a single human and a single robot, though this is certainly one important type of interaction. Robots used in search and rescue, for example, are typically managed by two or more people, each with special roles in the team [197, 264]. Similarly, managing Unmanned/Uninhabited Air Vehicles (UAVs) is typically performed by at least two people: a "pilot," who is responsible for navigation and control, and a sensor/payload operator, who is responsible for managing cameras, sensors, and other payloads [82, 182].

A question that has received considerable attention, but which is directly addressed by few scientific studies, is how many remote robots a single human can manage. In general, the answer is dependent on factors such as the level of autonomy of the robot (e.g., teleoperation requires a great deal of direct attention from the human), the task (which defines not only the type and quantity of data being returned to the human but also the amount of attention and cognitive load required of the human), and the available modes of communication.

In the search and rescue domain, Murphy [197] asserts that the demands of the task, the form factor of the robot, and the need to protect robot operators requires at least two operators, an observation that has received strong support from field trials using mature technologies [45], and partial support in search and rescue competitions using less mature but more ambitious technologies [264]. In other domains, some assert that, given sophisticated enough autonomy and possibly coordinated control, it is possible for a single human to manage more than one robotic asset [187, 190] though the task may still need another human to interpret sensor information. Still others assert that this problem is ill-formed when robots are used primarily as an information-gathering tool [121]. An intermediate position is that the right question should not focus on how many robots can be managed by a single human, but rather the following: how many humans does it take to efficiently manage a fixed number of robots, allowing for the possibility of adaptable autonomy and dynamic handoffs between humans [266].

One measure that has received some attention in the literature is the notion of *fan-out*, which represents an upper bound on the number of independent, homogeneous robots that a single person can manage [216, 217]. This measure is supported by a limited set of techniques for estimating it [68]. Some work has been done to refine the fan-out to apply to teams of heterogeneous robots [112] and to tighten the bound by identifying various aspects of interaction [190]. In its present form, however, it is clear that fan-out is only a designer guideline and is insufficient, for example, to provide a trigger strategy [144] for adaptive automation. Alternatives to fan-out include predicting the performance of a team of heterogeneous robots from measurements of neglect tolerance and interaction times [69].

In addition to the number of humans and robots in a team, a key problem is the organization of the team [98, 213]. One important organizational question is who has the authority to make certain decisions: robot, interface software, or human? Another important question is who has the authority to issue instructions or commands to the robot and at what level: strategic, tactical, or operational? A third important question is how conflicts are resolved, especially when robots are placed in peer-like relationships with multiple humans. A fourth question is how roles are defined and supported: is the robot a peer, an assistant, or a slave; does it report to another robot, to a human, or is it fully independent?

Spanning all of these questions is whether the organizational structure is static or dynamic, with changes in responsibilities, authorities, and roles. In one study, managing multiple robots in a search and rescue domain under either manual or coordinated control produced results that strongly favored coordinated control [308]. In another study, four autonomy configurations, including two variations of sliding autonomy, were managed by a human working on a construction task with a team of heterogeneous robots [266]. In this study, the tradeoffs between time to completion, quality of behavior, and operator workload were strongly evident. This result emphasizes the importance of using dynamic autonomy when the world is complex and varies over time. In a third study, researchers explored how making coordination between robots explicit can reduce failures and improve consistency, in contrast to traditional interfaces [147]. In a fourth study, researchers explored the minimal amount of gestural information required to command various formations to a team of robots [277].

In many existing and envisioned problems, HRI will include not only humans and robots interacting with each other, but also coordinating with software agents. The most simple form of this is a three-agent problem which occurs when an intelligent interface is the intermediary between a human and a remote robot [249]. In this problem, the interface agent can monitor and categorize human behavior, monitor and detect problems with the robot, and support the human when workload levels, environment conditions, and robot capabilities change. A more complicated form of this teaming is in anticipated NASA applications

where multiple distributed humans will interact with robots and with software agents that coordinate mission plans, human activities, and system resources [29].

A final issue that is starting to gain attention is the *role* of the human [262]. While much of the discussion up to this point is with respect to humans and robots performing a task together, there are cases where the robot may have to interact with bystanders or with people who are not expecting to work with a robot. Examples include the urban search and rescue robot that comes across a human to be rescued, a military robot in an urban environment that must interact with civilians, and a health assistant robot that must help a patient and interact with visitors. The role of the robot with respect to humans must be taken into account. The role of the human will be discussed in more detail in Section 5.

4.4   Adaptation, Learning, and Training

Although robot adaptation and learning have been addressed by many researchers, training of humans appears to have received comparatively little attention in the HRI literature, even though this area is very important. One reason for this apparent trend is that an often unstated goal of HRI is to produce systems that do not require significant training. This may be because many robot systems are designed to be used in very specific domains for brief periods of times [271, 292]. Moreover, robot learning and adaptation are often treated as useful in behavior design and in task-specific learning, though adaptation is certainly a key element of long-term interactions between humans and robots [104].

On one hand, it is important to minimize the amount of human training and adaptation required to interact with robots that are used in therapeutic or educational roles for children, autistic individuals, or mentally challenged individuals. On the other hand, it is important that HRI include proper training for problems that include, for example, handling hazardous materials; similarly the very nature of using robots in therapeutic and educational roles requires that humans should directly adapt and learn from the interaction [148]. In this section, we discuss not only HRI domains that require minimum operator training,

but also domains that require careful training. We also discuss efforts aimed to train HRI scientists and designers, and then conclude with a discussion of how the concept of training can be used to help robots evolve new skills in new application domains.

Minimizing Operator Training. Minimizing training appears to be an implicit goal for "edutainment" robots, which include robots designed for use in classrooms and museums, for personal entertainment, and for home use. These robots are typically designed to be manageable by a wide variety of humans, and training can range from instruction manuals, instruction from a researcher, or instructions from the robot itself [210, 275]. One relevant study explored how ROOMBA robots are used in practice without attempting to make operators use the robots in a specific way [99]. Such studies are important because they can be used to create training materials that guide expectations and alert humans to possible dangers. Other such studies include those that explore how children use education robots in classroom settings [148], investigate how disabled children interact with robots in social settings [23], support humans in the house [302], and identify interaction patterns with museum guide robots [210].

Complementing such studies are efforts to use archetype patterns of behavior and well-known metaphors that trigger correct mental models of robot operation. Examples include the often stated hypotheses that people with "gaming experience" will be able to interact better (in some sense) with mobile robots than those with limited experiences in games [241]. We are not aware of any studies that directly support this hypothesis, but if it is true then it would seem to suggest that people with experiences in video-conferencing, instant-messaging, and other computer-mediated forms of communication might more naturally interact with robots. Whether this hypothesis is true is a matter of future work, but it is almost certainly true that such experiences help people form mental models that influence interactions [238]. Designers are seeking (a) to identify interaction modes that invoke commonly held mental models [66] such as those invoked by anthropomorphic robots [156] or (b) to exploit fundamental cognitive, social, and emotional processes [32]. One possible caution for these efforts is that robots may

reach an "uncanny valley" where expectations evoked by the robot fall short of actual behavior producing an interaction that can feel strangely uncomfortable to humans [71, 194]. However, this uncanny valley theory is unproven although researchers are now trying to experimentally verify its existence [179].

Efforts to Train Humans. In contrast to the goal of minimizing training in edutainment robots, some application domains involving remote robots require careful training because operator workload or risk is so high. Important examples of such training are found in military and police applications, space applications, and in search and rescue applications. Training for military and police applications is typified by "bomb squad" robots, training for space applications is typified by telemanipulation tasks [234], and training for military and civilian search and rescue is typified by reconnaissance using small, "human-packable robots" [85]. In both the military and search application domains, training efforts exist for both air and ground robots, and these efforts tend to emphasize the use of mobile robots in a mission context [87]. Training efforts include instructions on using the interface, interpreting video, controlling the robot, coordinating with other members of the team, and staying safe while operating the robot in a hostile environment. Such training is often given to people who are already experts in their fields (such as in search and rescue), but is also given to people who may be relatively inexperienced. In the military, police and space domains, training programs may be complemented by selection criteria to help determine which indviduals are likely to be better (in some sense) at managing a robot [79]. Selection appears to have received more attention in air robots than ground robots.

By contrast to interactions with remote robots, many applications involving proximate robots are designed to produce learning or behavioral responses with humans. Therapeutic and social robots are designed to change, educate, or train people, especially in long-term interactions [148, 245, 312]. People also adapt to service robots over the long-term and over a wide range of tasks [115], and there is growing evidence that many long-term interactions require mutual adaptation including with human bystanders [75, 131, 117]. Importantly, culture

appears to influence both long-term and short-term adaptation, at least as far as accepting interactions with a robot [18, 94, 127, 150, 270, 306].

Training Designers. Importantly, an often overlooked area is the training of HRI researchers and designers in the procedures and practices of those whom they seek to help. Important examples of training researchers include Murphy's workshops on search and rescue robotics [198], tutorials and workshops on methodologies for understanding a work-practice domain and field studies [58], tutorials for young researchers on search and rescue [239, 240], and tutorials and workshops on metrics or experiment design for robot applications [294].

Training Robots. It is tempting to restrict training to the education of the human side of HRI, but this would be a mistake given current HRI research. In HRI, robots are also learning, both offline as part of the design process [37, 207] and online as part of interaction, especially long-term interaction [89, 251]. Such learning includes improving perceptual capabilities through efficient communication between humans and robots [33, 89, 251, 330], improving reasoning and planning capabilities through interaction [295, 34], and improving autonomous capabilities [258]. Approaches to robot learning include teaching or programming by demonstration [13, 55, 76, 77, 146, 218], task learning [34, 251, 207], and skill learning including social, cognitive, and locomotion skills [11, 22, 202, 233, 295]. Some researchers are exploring biologically inspired learning models, including how teaching among humans or social animals can be used to train a robot [11, 257]; others are exploring how learning can become more efficient if it leverages information about how the human brain learns in very few trials [100].

Interestingly, it can be argued that providing support for efficient programming or knowledge management systems is an important aspect of training robots in HRI [120, 327]. Additionally, it can be argued that sensitizing a robot to issues of culture and etiquette allows them to adapt to slowly changing human norms of behavior [141, 215, 252].

4.5   Task-Shaping

Robotic technology is introduced to a domain either to allow a human to do a task that they could not do before, or to make the task easier or more pleasant for the human. Implicit in this assertion is the fact that introducing technology fundamentally changes the way that humans do the task. Task-shaping is a term that emphasizes the importance of considering how the task should be done and will be done when new technology is introduced. Compared to the other ways that a designer can shape HRI, there is little written about task-shaping.

There are formal processes for understanding how the task should be done and is currently done. These processes include goal-directed task analyses, cognitive work analyses, and ethnographic studies [58, 88, 301]. Although frequently used to specify how a task is done and how it should be done, it is imperative to consider how the task will be done, including unintended consequences of design [14, 212].

One reason that little is written about task-shaping is because designers are implicitly trying to create technology and interactions that accomplish some task or function. Indeed, Woods has persuasively argued that designing a system is equivalent to making a hypothesis about how the artifact will positively shape the experience [319]. Nevertheless, it is important to consider how the task might be modified to better support interaction. Examples of explicit task-shaping include designing space or underwater equipment and tools so that handles and connectors can be manipulated by a robotic arm, "pre-cleaning" a room so that a robot vacuum can accomplish its task most efficiently [99], and performing pre-inspection tasks used to form maps and plans that can be executed by a robot.

4.6   Finding a Unifying Theme

There are multiple ways to frame HRI as a field. One approach is to treat HRI as a resurgent emphasis and extension of previous work in human factors, teleoperation, and supervisory control. Another approach to framing HRI is to view it as a new field that includes a con-

vergence of previous work with new research problems caused by some new capability that fundamentally changes the problem. We assert that robot autonomy has reached the point where mixed-initiative interaction and semi-autonomous control have fundamentally changed the field from previous research on related problems. Thus, we treat HRI as a new field that faces opportunities and problems which are not simple extensions of previous work. We acknowledge, however, that it is possible to make persuasive arguments that HRI is simply a refocusing of previous efforts rather than a new field.

One way to unify the scope of current HRI research is to condense the five dimensions of designer influence into a single concept as exemplified in our proposed scale of interaction, Figure 4.2, with the caveat that this single concept cannot capture every nuance and possible design of every HRI problem. The concept of *dynamic interaction* seems to capture the current research direction of many HRI efforts.

Dynamic interaction includes time- and task-varying changes in autonomy, information exchange, team organization and authority, and training. It applies to both remote and proximate interactions, including social and physical interactions. By including variable autonomy assignments, the concept of dynamic interaction subsumes adaptive and dynamic autonomy as a special case [80, 96, 97, 111, 144, 165, 259]. By including information exchange, dynamic interaction includes adaptive and adaptable interfaces [144, 153, 221]. By including team organization and authority, mixed initiative interaction [43, 98, 162, 226] is addressed. By including training, interactive learning is included.

More importantly, the concept of dynamic interaction places the emphasis on shaping the types of interactions that can and will emerge as humans and robots interact. The scope of HRI research and design, therefore, includes all efforts at evaluating systems and interaction paradigms, designing autonomy algorithms in the context of HRI, designing interfaces and information exchange protocols, defining and switching roles, and influencing learning and training. This emphasis on dynamic interaction differs sharply from the historically static interactions of pure teleoperation and pure supervisory control.

Note that some current research efforts and methods do not naturally fit into the dynamic interaction framework. These include several aspects of task shaping, including ethnographic studies, goal-directed task analyses, and some cognitive science-based work. However, understanding existing processes and potential use patterns helps researchers better understand the fluid interaction patterns that are likely to exist in practice so that they can design interactions that support, improve, and extend these interaction patterns.

5

Problem Domains in HRI

We have already mentioned several of the problem domains and application areas in modern HRI. In this section, we elaborate on many of these problem domains to present a survey of the kinds of problems encountered in HRI. Importantly, many of these problems have broad social impact; thus, much work in HRI uses science and engineering to respond to needs in society.

Scholtz provided a taxonomy of roles that robots can assume in HRI [262]:

- Supervisor,
- Operator,
- Mechanic,
- Peer, and
- Bystander.

To this list, we add the following:

- Mentor: the robot is in a teaching or leadership role for the human, and

- Information Consumer: the human does not control the robot, but the human uses information coming from the robot in, for example, a reconnaissance task.

Similar taxonomies are certainly possible, but identifying how people perceive a robot's role has important ramifications for how they interact with the robot [74]. Using Scholtz's taxonomy provides insight into the current and future interactions in these applications. Table 5.1 classifies the most frequent types of interactions for the application areas discussed in the remainder of this section. For many of these areas, current research patterns exhibit a trend away from remote interactions

Table 5.1 Examples of roles and proximity patterns that arise in several application areas.

Application area	Remote/ Proximate	Role	Example
Search and rescue	Remote	Human is supervisor or operator	Remotely operated search robots
	Proximate	Human and robot are peers	Robot supports unstable structures
Assistive robotics	Proximate	Human and robot are peers, or robot is tool	Assistance for the blind, and therapy for the elderly
	Proximate	Robot is mentor	Social interaction for autistic children
Military and police	Remote	Human is supervisor	Reconnaissance, de-mining
	Remote or Proximate	Human and robot are peers	Patrol support
	Remote	Human is information consumer	Commander using reconnaissance information
Edutainment	Proximate	Robot is mentor	Robotic classroom assistant
		Robot is mentor	Robotic museum tour guide
		Robot is peer	Social companion
Space	Remote	Human is supervisor or operator	Remote science and exploration
	Proximate	Human and robot are peers	Robotic astronaut assistant
Home and industry	Proximate	Human and robot are peers	Robotic companion
	Proximate	Human is supervisor	Robotic vacuum
	Remote	Human is supervisor	Robot construction

toward proximate interactions, and away from operator roles toward peer or mentor roles.

5.1   Search and Rescue

The highest profile HRI research area in the United States is a strong example of work with important social impact. This area is urban search and rescue (USAR), and is exemplified by the use of robots in rescue and recovery efforts after the collapse of the World Trade Center buildings [51]. Lead by pioneering government and academic efforts [26, 200], USAR has grown into one of the most important areas of HRI.

Because of its importance, USAR has become an HRI challenge problem. As such, there have been efforts to provide standardized USAR test areas and performance measures, and to standardize robot-assisted USAR efforts [138, 199, 263]. There are regular USAR competitions at robot-related conferences [159, 199, 325]. A wide variety of interface concepts, autonomy designs, sensor-processing algorithms, robot morphologies, field studies, and human factors analyses and experiments have been created in the name of robot-assisted USAR (see, for example, [197, 198, 211, 264, 318]). Recently, these efforts are being extended from ground robots to include aerial robots used in natural disaster and wilderness search [61, 278].

5.2   Assistive and Educational Robotics

In the spirit of socially relevant research, robots are being developed to serve in assistive and educational capacities. Assistive robotics is perhaps one of the highest profile areas of HRI in the world. This application domain often places the robot in a peer-like or mentoring role with the human in practice, even though the intention of the robot is designed to provide service to the human. For example, robots being developed to assist the visually challenged work in close proximity to humans and must merit an appropriate level of trust. The goal of work in this area is to increase the set of tasks that a visually impaired person can independently perform. These tasks include providing naviga-

tion assistance in unstructured domains [167, 170, 274], and providing information about locations (and prices) in grocery stores and transportation facilities [168].

Another important area of research, especially in countries with a burgeoning population of the elderly, is providing support for those who have age-related challenges [192, 231, 232, 252, 304]. Researchers in this area focus on both physical needs such as mobility assistance [324], emotional welfare [252, 303], and cognitive assistance [151]. Many working in this area are fully aware of the ethical considerations that arise by delegating a companionship role to a robot and the trust issues that arise by having an artificial agent working with someone with mental challenges such a senility [286]. Having the ability to remotely manage a personal assistant robot over the internet may be a step in the direction of addressing these ethical concerns, though substantial technological and privacy limitations exist for such interaction [166].

For some people with physical and mental challenges, robots may provide an opportunity for interaction and therapy. Such work is being explored with autistic children [23, 247]. Many of these children respond weakly or not at all to social cues, but respond well to mechanical devices. Robots provide a possible therapeutic role for using a mechanical device to improve social interactions [312]. Robots are also being considered for other domains where children are benefited, such as those who have experienced trauma. Importantly, the social dimension of HRI is considered necessary not only in assistive roles but also in many areas of proximate interaction [31, 32, 72, 90, 106, 148]. Indeed, the area of social robotics is so large that it is already time to update the highly cited 2003 survey [94].

For some people with physical challenges, the embodiment of a robot provides unique opportunities not available in other forms of technology. For example, researchers are working on designing robots that provide support for physical therapy. Efforts include providing prescribed force and movement trajectories to help rebuild flexibility and strength [178]. Other work includes detecting motivational state and adjusting therapy to maximize benefits [236]. Intelligent wheelchairs are a type of robot that uses external sensors to support path planning, collision avoidance, etc. for a person that requires a wheelchair [134, 324].

Physical interaction with robots is not limited to providing assistance to those with some form of disability. Many robot architectures have been designed to assist humans in industrial settings [228]. Indeed, developing telerobots for use in hazardous materials handling has been ongoing for several decades [139]. However, cooperative systems are not limited to large-scale industrial settings, but may be most useful in small-scale tasks "such as microassembly and microsurgery" [180]. The technologies developed for such assistive support appear to apply not only to proximate physical interaction, but also to the general telemanipulation problem [224].

In the spirit of providing assistance to those without a disability, some researchers are also exploring how robots can be used to promote education for typical children, both in the home and in schools [62, 140]. The personal service robot is an extension to the theme of providing service to the general population. Indeed, South Korea has ambitious goals about the advancement of such robots [219].

5.3 Entertainment

Although there have been many examples of entertainment robotics, from an HRI perspective, not much has been published in the literature. Early entertainment robotics centered on animatronics, where the robot generally plays prerecorded sounds that are synchronized with the robots motion. These types of robots can often be found in old movies and theme parks; however, the interaction is mostly in one direction, that of the robot presenting information, although the robot's performance may be triggered by the presence of the human. However, the 2005 AICHI Expo demonstrated several robots designed to entertain, including the use of robots as actors and dance partners [6]; similar work on the relationship between acting, drama, and artificial agents is presented in [41]. Here again, the role of the human is as an observer, and the interaction is minimal and more implicit [41].

The Valerie and Tank robots at Carnegie Mellon University were designed as robot receptionists as a joint project between CMU's Robotics Institute and the School of Drama [106]. The robots have a rich back story and strive to increase users' interaction by encouraging

the user to ask about the robots' lives outside of their role as receptionists. Although robots that act as tour guides might be considered a form of assistive robotics, we classify such robots under the category of entertainment because their primary role is to engage participants [120, 210].

Although not strictly entertainment, the Insect Telepresence project [8] placed Madagascar Hissing Cockroaches in a terrarium, and allowed users, through mediated telepresence, to drive a miniature camera within the terrarium, at eye level to the cockroaches. The image from the camera was projected much larger than life on a wall. Of interest was the mediated teleoperation, which limited the accelerations of the camera motions to below that which would cause the cockroaches to react to the camera, offering the humans a look into the cockroach's world.

Other HRI-related research in the use of robots for entertainment include robotic story tellers [191], robotic dance partners [163], robotic plants that give users information such as incoming email [137], and robotic pets [94, 272].

5.4   Military and Police

Many have called for robots to be used in tasks that are "dull, dirty, or dangerous." Military and police applications often simultaneously satisfy all three criteria for robot use. Applications include gathering information to support a dangerous task such as a SWAT team take-down, or using remote vehicles in combat to minimize risk exposure to soldiers. Current work emphasizes robots as servants to soldiers and officers [87], typically in remote operations, but efforts to have robots work in a peer-like role are underway [44, 155].

A typical use of robots in both military and police applications is in bomb disposal (called "improvised explosive devices" in many military situations) [263]. Remotely controlled robots are frequently used to approach and evaluate suspicious packages [311]. Controlling these robots is demanding on the operators, especially since many current interfaces and autonomy levels require operators to integrate information from multiple sources of data such as multiple cameras. In addition

to controlling mobile platforms, telemanipulation is an important part of such work. Robot arms are often mounted on the platforms providing operators some ability to manipulate the object. Because of the limited situation awareness for controlling these arms, some researchers are exploring sensor technologies and information presentation techniques that improve awareness in telemanipulation [242].

5.5 Space Exploration

Robots have long been part of space exploration. In fact, according to some definitions, a satellite can be considered a type of robot, albeit one that has a high degree of autonomy and typically requires minimal intervention.

As has been previously noted, remarkable success in space robotics include the Soviet Lunokhods which were used to explore the surface of the moon [95] followed by more recent NASA success in exploring the surface of Mars [174, 317]. It is anticipated that the robots will continue to have a strong role in envisioned and future explorations of the lunar and Martian surfaces, in construction tasks on these surfaces as well as in the international space station, and in remote science and maintenance tasks [84, 129, 177, 225].

Many precursor and early human missions will depend heavily on remotely managed robots, but will also likely include extravehicular activities. To prepare for these missions, NASA and other international space agencies engage in frequent field work designed to evaluate both the robotic and HRI technologies. Examples of this include development of the Dante robots [16, 17], a series of Extra-Vehicular Activities (EVA)-based field tests [47, 114, 296], and field tests involving substantial communications delays and remote science in harsh environments [283, 310]. Research that extends these efforts includes the aforementioned Robonaut development and work on developing intelligent rovers and robot "mules" to pack astronaut equipment on long duration EVAs.

Complementing the focus on remote and EVA-based interaction are efforts to support astronauts at the international space station and on long duration space missions. These efforts focus on astronaut

assistants and small satellites [54, 81]. Many of the NASA programs include strong planning components and seek to integrate software, robotic, and human agents [30]. Other work calls for standardization of robot parts, procedures, communications, and interfaces [91, 92].

5.6   UAV Reconnaissance and UUV Applications

Unmanned Air Vehicles are rapidly attracting attention as an application area for HRI and for aviation technology. UAVs have been around for a long time and have a large body of related literature, but the label for such vehicles varies over time. Among other labels, UAV work has been published under names like remotely piloted vehicles, uninhabited air vehicles, autonomous micro air vehicles, and autonomous aerial systems. The key defining aspect of UAV interaction is the fact that the vehicles are, by definition, remotely operated, move in three dimensions, and typically have six degrees of freedom. Interestingly, remote interactions and a high degree of freedom are also defining attributes for problems that use Unmanned Underwater Vehicles (UUVs), often referred to as autonomous underwater vehicles. Because of this similarity, we unite our discussion of these two important areas of HRI. This unification may be particularly relevant because the literature from these two communities rarely overlaps even though the interaction dynamics have marked similarities.

In addition to the previously mentioned reconnaissance-based military and search-and-rescue uses of UAVs, there are a number of other envisioned uses of these vehicles. These include atmospheric science [107], landing site surveillance of a Mars rover [19], border patrol [103], pollution monitoring [113], forest fire monitoring [49], infrastructure inspection [113], and munitions-based military applications [70]. UUVs have similarly broad areas of use. They include undersea science, treasure hunting, undersea and surf-zone de-mining, and underwater construction and maintenance [329]. For remote operations, there are many interface designs that apply to both UAV and UUV operations. These include integrating multiple perspectives, developing a sense of telepresence, synchronizing frames of reference through tethers, and building mosaics [101, 230].

5.7   Other Applications

There are a host of other application domains where robots are used. These domains include home use, manufacturing, inventory management, mining, and precision agriculture. Importantly, some of these application domains include strong HRI research, but others attempt the creation of "fully autonomous" robots that do not require human interaction and, ironically, are not "autonomous enough" to allow interaction with humans. Although it is possible that some of these domains might allow "fire-up and forget" robots, it is likely that the usefulness and safety of robots in many of these domains will increase if HRI considerations are included in their design.

6

Solution Themes, Scientific Approaches, and Challenge Problems

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One measure of the maturity of a research field is the emergence of a series of accepted practices and challenge problems that focus the attention of the field. Equally important is the identification of solution themes that cross applications. In this section, we survey several practices, challenge problems, and solution themes.

6.1 Accepted Practices

There are a number of accepted practices that are emerging in HRI. A key practice is to include experts from multiple disciplines on research efforts. These disciplines frequently include robotics, electrical and mechanical engineering, computer science, human–computer interaction, cognitive science, and human factors engineering. Other relevant disciplines include design, organizational behavior, and the social sciences. Importantly, some conferences encourage multidisciplinary submissions are working to establish the practice of having all papers refereed by reviewers representing different disciplines [265].

A second emerging practice is to create real systems (robot autonomy, interaction modes, and etc.) and then evaluate these systems

using experiments with human subjects. Proof-of-concept technologies, although important, are less valuable than they would be if they were supported by careful experiments that identify key attributes of the design or principles that span applications. Identification of descriptive interaction phenomena is interesting, but elaboration on the psychological principles underlying these phenomena with an eye toward harnessing these principles in design is more useful. Thus, engineering, evaluation, and modeling are key aspects of HRI.

A third emerging practice is conducting experiments that include a careful blending of results from simulated and physical robots. On the one hand, because of cost and reliability issues, it is often difficult to conduct carefully controlled experiments with physical robots. On the other hand, it is often difficult to replicate simulation-only results with physical robots because the physical world presents challenges and details that are not present in many simulations. It is common to "embody" at least one portion of the interaction, be it a physical robot, some physical sensor, or real-world speech. Some research includes work using carefully controlled simulation environments and replication of selected results with physical robots. Others use wizard of Oz studies. Others form communities where roboticists design technologies and where other human factors researchers collect and analyze results from tests; this is the operating structure of part of the robot-assisted urban search and rescue (USAR) community [325]. Interestingly, at least one research group is exploring how a simulated user can help support the design of human–robot interfaces [244].

A fourth area of emerging effort is establishing standards and common metrics. The most complete survey of metrics is in [280], but much work on metrics exists in the literature including the proceedings of the annual PERMIS workshops. Standardization efforts have been strongest in the USAR domain [138, 199], but are also present in space applications and UAVs [91, 92].

A fifth emerging practice is the use of longitudinal studies. Such studies, which can last from several weeks to several months, require a considerable investment by researchers, both in terms of hours and financial resources. One reason that long-term studies are a relatively recent practice is that many robots were not reliable enough

to work over the study period. The availability of reliable personal home robots and service robots in public areas has made such studies possible [99, 120]. The European COGNIRON project is a good example of a commitment to long-term studies [59]. Long-term studies shift research methodologies from carefully controlled small-scale experiments to other methodologies such as surveys and ethnography.

6.2   Challenge Problems

It is often useful to identify a set of challenge problems that focus the efforts of a community. HRI has a suite of challenge problems, some explicitly identified as such and others implicitly operating as such. In this section, we identify a collection of problems that are likely to shape HRI in the near future. For each problem, we discuss those aspects of the problem that make it particularly challenging and useful.

USAR is the most high profile of the HRI challenge problems. The attributes that define this as a challenge problem include the highly unstructured nature of USAR environments. This imposes strict challenges on robot mobility, communications, map-building, and situation awareness.

Developing robots to be used in **military** reconnaissance and combat is another high profile challenge area in HRI. Similar to USAR, environments tend to be unstructured, but perhaps more importantly operators may be required to operate under extreme stress in the presence of an adversary that is trying to prevent their success.

Space robotics is another area where the environment is often unstructured, and the environment is often extreme in terms of temperature, radiation, the vacuum of space, and the presence of dust. Important characteristics of space robotics include the observation that operators can be highly trained, but communications may be very limited due to time delays, power limitations, and even operator mobility (as in the case of an astronaut interacting from within a space suit).

Assistive robotics is a challenge area, but not because the environment is unstructured *per se.* Rather, the key attributes of this problem

are the proximity and vulnerability of the human in the interaction plus the potential for interactions that may evolve in unanticipated patterns.

Humanoid robotics is a challenge area, both in terms of engineering human-like movements and expressions, and in terms of the challenges that arise when a robot takes a human form. With such a form, social and emotional aspects of interaction become paramount.

Natural language interaction is a challenge problem, not only because it requires sophisticated speech recognition and language understanding, but also because it inevitably includes issues of mixed-initiative interaction, multi-modal interaction, and cognitive modeling.

6.3   Solution Themes

HRI presents a number of problems that cross application domains. These problems include requirements on autonomy, information sharing, and evaluation. Emerging from these problems are a set of solution themes that cross applications and that, when addressed, can be leveraged across several problems. In this section, we identify some of these solution themes and discuss some of the open questions associated with them.

Dynamic Autonomy, Mixed-Initiative Interaction, and Dialog. Because most interesting applications of human–robot interaction include rich information exchanges in dynamic and complex environments, it is imperative that interactions and resulting behaviors can accommodate complexity.

Telepresence and Information Fusion in Remote Interaction. Although remote control and teleoperation are the oldest forms of human–robot interaction, the problem is far from solved. In fact, with advances in robot morphology, sensor processing, and communications, it is necessary to find new ways to fuse information to provide humans an operational presence with the robot. Obstacles to achieving this include bandwidth limitations, communications delays and drop-outs, mismatches in frames of reference, communicating intent and trusting autonomy, and mismatches between expectations and behaviors.

Cognitive Modeling. Effective interactions between humans include a common ground created by common experiences and cultures. This common ground creates realistic expectations and forms the basis communications. From a robot's perspective, supporting effective interactions also requires establishing and maintaining common ground. An emerging approach to doing this is to create cognitive models of human reasoning and behavior selection. The goal is to create rich enough models either (a) to allow the robot to identify a human's cognitive state and adjust information exchange accordingly or (b) to allow the robot's behavior to be generated by models that are interpretable by a human.

Team Organizations and Dynamics. Many HRI researchers are striving to develop systems that allow multiple robots and multiple humans to interact with each other. To accomplish this, it is necessary to shape team interactions and dynamics by establishing organizational structures, communications protocols, and support tools. Team organizations necessarily subsume different and dynamic roles, which implies that such efforts will need to leverage lessons from research on mixed initiative and dialog.

Interactive Learning. Because the world is complex, interactions between humans and robots are also complex. This implies that it is impossible to anticipate every conceivable problem and generate scripted responses, or anticipate every conceivable percept and generate sensor processing algorithms. Interactive learning is the process by which a robot and a human work together to incrementally improve perceptual ability, autonomy, and interaction.

7

Relation to Other Fields

Although we have framed HRI as a new field in this review, HRI has strong ties to previous and ongoing work in telerobotics, intelligent vehicle systems, human–computer interaction, etc. In this section, we review many of the stronger ties to these fields. We begin with the most relevant: telerobotics and supervisory control.

7.1   Telerobotics and Teleoperation

Sheridan's papers and books on telerobotics and supervisory control are perhaps the most influential in the field. In 1992, his book outlined the state of the art in human–robot interaction, with an emphasis on open problems, mathematical models, and information flow [267]. This book was followed by a 2002 updated survey and framework of human factors for the general human–machine interaction problem [268].

Even more influential than his books, perhaps, is Sheridan's and Verplank's levels of automation in human–machine interaction. These 10 levels of automation span the range from direct control through decision support to supervisory control [269]. More recently, Parasuraman and Wickens teamed with Sheridan to extend these 10 levels of automation beyond decision support to other aspects of human–machine

interaction [248]. Levels of automation foreshadow more recent concepts of dynamic autonomy in all its forms [67, 144].

In addition to these seminal works, there are numerous examples of remote robot operation. One example comes from attempts during World War II to remotely control aircraft. This lead to the study of remotely piloted vehicles [95], a precursor of more modern work on the Human Factors of Unmanned/Uninhabited Aerial Vehicles [322].

Complementing the work on remotely piloted aircraft is a work on unmanned underwater vehicles (UUVs). This work includes both military and scientific applications, and spans topics of remote visualization, telepresence, and information display [329].

7.2   Human Factors and Automation Science

The field of human factors emerged as the confluence of engineering psychology, ergonomics, and accident analysis. Human factors work relevant to HRI includes important lessons from thought provoking papers such as Bainbridge's "Ironies of Automation" [14] and Hancock's position paper on the make-up of HRI teams [121]. Human factors work is motivated by numerous stories, sometimes humorous and sometimes sobering, from years of humans interacting with automation in various forms [50].

The human factors literature has produced key concepts of interaction, such as mental workload [110, 204], situation awareness [88], mental models [142, 300], and trust in automation [173]. It also includes several themes, frameworks, and models that provide a solid foundation for describing and predicting responses to human–robot interaction. These contributions include the seminal work of Rasmussen who presented a hierarchy of interaction that included knowledge-based, rule-based, and skill-based interactions [237]. Rasmussen's hierarchy is a human factors complement to hierarchical and intelligent control [7, 183, 255]. Contributions also include general principles of cognitive ergonomics, with particularly powerful ideas such as Wickens's Multiple Resource Theory [314]. Complementing these models are interaction phenomena that are common enough that they are elevated to the status of law by David Woods [320].

Rich as these models and laws are, they cannot substitute for practical real-world observation. This point was strongly made by Hutchins in the book "Cognition in the Wild" [130]. In the spirit of real-world observation, the field of ethnography has developed a set of methodologies for recording observations in real-world settings, and some ethnographers have tried to translate these observation and summarization methods into tools for designing interventions [57, 58, 93].

Growing out of the need to understand the goals, tasks, and information flow of existing processes, a series of methodologies have emerged that produce formalized models for how "things get done." These methodologies include Goal-Directed Task Analysis, Cognitive Task Analysis, and Cognitive Work Analysis [88, 301]. These methodologies produce models of goals, tasks, and information flow, which are being used in HRI [4]. Complementing these high-level models are cognitive models of the mental processes used to accomplish tasks, and activity analyses of existing work practices. The cognitive models and activity analyses are especially interesting to HRI because they can be used not only as models of existing processes, but also as tools to generate behaviors such as perspective-taking and planning [295].

It is worth noting that cognitive psychology and social psychology offer perspectives and insights that are distinct from traditional human factors. There is a trend in HRI to include cognitive and social scientists in collaborative research efforts with roboticists, human factors engineers, and experts in human–computer interaction.

Given the rich history of human factors and the recent emergence of HRI, it is unfortunate and perhaps inevitable that some relevant human factors work is called by different names in the different fields. Examples include adjustable autonomy and Inagaki's Situation-Adaptive Autonomy [132, 133]; and augmented reality/virtuality and synthetic vision [48].

7.3 Aviation and Air Traffic Control

Modern aircraft are among the most capable semi-autonomous systems in use. Moreover, because of the safety critical nature of aviation, aircraft systems must be extremely robust and reliable. Careful human

factors analyses are often performed to justify a change to an aircraft system. From one perspective, an aircraft is a very capable type of robot, albeit one that happens to carry the human operator.

As a result, HRI has many lessons that it can learn from aviation, both in terms of useful technologies and careful human factors analysis. Relevant examples include ground proximity warning systems, which use multi-modal communications coupled with robust autonomy to prevent controlled flight into terrain [63]. Tunnel-in-the-sky displays can increase situation awareness by helping pilots to understand how control choices will affect the trajectory of the aircraft [195]. Problems caused by mode confusion, by the operator being out of the loop, by vigilance, by excessive workload, and by team coordination issues have all received attention and been mitigated by procedures and technologies.

As robots become more capable, an important issue is how many robots can be managed by a single human. This question makes another aspect of aviation relevant to HRI, namely, human factors work done with the air traffic control problem (ATC). ATC is a problem that involves sequencing, deconflicting, and handing off multiple highly capable systems [123]. Indeed, the autonomy level of these aircraft is extremely high, since they consist of both a trained and intelligent human operator as well as aircraft autonomy. Nevertheless, ATC imposes high workloads on operators. Careful human factors analyses have been performed and mitigating technologies have been developed [86, 214]. Because of the safety critical nature of ATC, many potentially useful technologies have not been incorporated into ATC systems. Even so, some ATC-related research and development could serve as a type for HRI problems.

There are three other aspects of aviation and ATC that are very relevant to HRI. First, ATC training and certification programs have many desirable attributes that could be imitated in HRI. Second, because aviation incidents are relatively rare and, when they occur, can damage career prospects, the aviation industry has developed anonymous reporting procedures which are kept in a database of problems that have occurred. As HRI matures, it could be useful to create a standardized reporting system to identify and mitigate problems that frequently arise. Third, the aviation industry has a strong set of standards. There

have been recent efforts to bring the standardization process to HRI [92], though it is important that these efforts do not impose undue restrictions on creativity and design.

7.4   Intelligent Vehicle Systems

The field of intelligent vehicle systems (IVS) has received considerable attention in recent decades, including the emergence of several conferences and journals [1, 2, 3, 288]. The field of intelligent vehicle systems has many problems in common with HRI, including designing autonomy that supports human behavior, creating attention-management aides, supporting planning and navigation under high-workload conditions, mitigating errors, and creating useful models and metrics [27, 108, 109]. Indeed, a strong case can be made that modern automobiles are just semi-autonomous robots that carry people.

IVS not only include automobiles, but also trains, busses, semi-trucks and other forms of public transit [25]. The users of IVS range from those that are highly trained to those that are untrained and sometimes even uninformed. Moreover, IVS must be designed to be safety-critical, time-critical, and to operate under high workload conditions. The presence of untrained operators and high-demand tasks produces technologies that may be relevant for those aspects of HRI that require interaction with bystanders or naïve operators.

7.5   Human–Computer Interaction (HCI)

As the field of HRI has grown, it has seen many contributions from researchers in HCI and it has been nurtured by HCI organizations. For example, the first International Conference on Human–Robot Interaction was sponsored by ACM's Computer–Human Interaction Special Interest Group [265]. HRI research is attractive to many members of the HCI community because of the unique challenges posed by the field. Of particular interest is the fact that robots occupy physical space. This offers unique challenges not offered in desktop metaphors or even pervasive computing. Physical location in a 3D space imposes strong requirements on how information is displayed in remote operation, and

even stronger requirements on how space is shared when robots and humans occupy the same space. HRI benefits from contributions from HCI researchers, both in methodologies, design principles, and computing metaphors.

7.6 Artificial Intelligence and Cybernetics

Because of their emphasis on designing intelligence for human-built systems, the fields of artificial intelligence (AI) and cybernetics have a great deal of relevance to the field of HRI. Intelligence and autonomy are closely aligned. Indeed, when experimenters want to give the illusion of truly intelligent robots, it is common to use a "wizard of Oz" design wherein experiment participants believe that they are controlling an intelligent robot but where in reality the commands that they issue are received and translated into teleoperation commands by a hidden human [116].

HRI frequently uses concepts from AI in the design of autonomy algorithms. Moreover, AI techniques have informed and been informed by concepts from cognitive science. For example, the ACT-R system, a popular tool for modeling cognition, uses AI-like production rules. Such cognitive models have increasingly become relevant to HRI, both as tools for modeling how a human might interact and as the basis for generating robot behavior [295].

Although sometimes justifiably treated as a separate field from AI, augmented reality and telepresence have much relevance to HRI. Augmented reality techniques are used to support remote interactions in NASA's Robonaut [9]. Augmented virtuality and mixed reality are variations of augmented reality that have found application in HRI [208]. Some suggest that telepresence, the natural extension of human awareness of a remote space, is a goal of interface design in HRI, though others note that a feeling of remote presence is not necessary provided that information is displayed in a way that supports intentional action in the remote space [208].

Another AI-related area that has developed into a separate field of study is computer vision. Computer vision algorithms are frequently used to translate camera imagery into percepts that support autonomy.

Moreover, these algorithms are also used to provide enhanced awareness of information through the use of image stabilization, mosaics, automated target recognition, and image enhancement.

Many AI techniques are used in computer games. These games, some of which are very sophisticated, provide a probe into the levels of autonomy needed to support useful interactions. Given these levels of autonomy, information is integrated and presented to operators in several different forms; evaluating these forms of information presentation provides guidelines for interface designers in HRI [241]. Sophisticated multi-player online games may become useful in understanding how natural language can be used to support HRI and how human–robot teams should interact.

Finally, machine learning is a subfield of AI that is proving very useful in robotics and HRI. Machine learning can be used to develop robot behaviors, robot perception, and multi-robot interaction [40, 89, 207]. Interactive learning has received attention as a way to capture and encode useful robot behaviors, to provide robot training, and to improve perception. Interactive techniques with intelligent systems are also present in AI. Interactive proof system, interactive planners, and "programming by reward" in machine learning are all examples of how human input can be used in collaboration with AI algorithms.

7.7   Haptics and Telemanipulation

Before concluding the review, it is important to note that much of the field of haptics and telemanipulation are aligned with the goals and challenge problems of HRI. However, the current research culture tends to treat haptics/telemanipulation separate from HRI, perhaps because of the longer history of the field of haptics. Since the two fields have much to learn from each other, it is desirable that the research communities increase interactions.

8

Summary

Human–robot interaction is a growing field of research and application. The field includes many challenging problems and has the potential to produce solutions with positive social impact. Its interdisciplinary nature requires that researchers in the field understand their research within a broader context. In this survey, we have tried to present a unified treatment of HRI-related problems, identify key themes, and discuss challenge problems that are likely to shape the field in the near future.

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