

A Taxonomy for Human-Robot Interaction

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Abstract

This paper integrates research and ideas in the fields of Human-Computer Interaction and Robotics for the creation of a taxonomy for human-robot interaction. By drawing from multiple research fields, a more complete taxonomy is attained. Taxonomy categories include team composition (ratio of people to robots, types of robots), amount of required interaction, decision support provided for the user, and space-time location.

Introduction

Human-robot interaction currently takes many forms. Dangerous tasks, such as urban search and rescue [Casper 2002, Casper and Murphy 2002] and hazardous material clean up [Bruemmer, Marble and Dudenhoffer 2002], require a human operator to be removed from the physical location of the robot. Robots that assist the elderly [Haigh and Yanco 2002] and the handicapped [Mittal et al. 1998] share the same physical space with their users, often transporting them through the world. Others, such as Sony's Aibo, provide entertainment and companionship for people.

We maintain that human-robot interaction (HRI) is a subset of the field of human-computer interaction (HCI). HCI has been defined in many ways. One example is the definition used by the Curriculum Development Group of the Association for Computing Machinery (ACM) Special Interest Group on Computer-Human Interaction (SIGCHI): "Human-computer interaction is a discipline concerned with the design, evaluation and implementation of interactive computing systems for human use and with the study of major phenomena surrounding them" [Hewett et al. 1992]. Since robots are computing-intensive systems designed to benefit humans, we feel that HRI can be informed by the research in HCI. Accordingly, we bring an HCI perspective to our discussion of HRI taxonomies.

HRI can also be considered a subset of the field of computer-supported cooperative work (CSCW), "an identifiable research field focused on the role of the computer in group work" [Grief 1988]. Often teams of people work with one or more robots, clearly putting the human-robot system in the realm of CSCW. Even when a human-robot system is comprised of only one human and one robot, this human-robot system can be considered to be

engaged in CSCW if the robot is viewed as an (unequal) partner to the human. Thus, we have also mined the CSCW literature for relevant inputs to our taxonomy work.

The robotics field also provides inspiration for a taxonomy of human-robot interaction, as most robot systems are interacting with humans at some level. Some formal study of this interaction has already begun [Murphy and Rogers 2001]. Additionally, the multi-agent robotics has been investigating issues involved with teams of robots and their interactions for many years [Balch and Parker 2002].

Related Taxonomies

Some taxonomies for human-computer interaction, robotics and human-robot interaction have already been proposed in the literature. This paper proposes what we believe to be a complete taxonomy of human-robot interaction; in order to do so, we must build upon taxonomies that already exist in the fields of human-computer interaction and robotics. This section describes the other taxonomies in the literature and discusses their applicability to our proposed taxonomy.

Human Interactions with Intelligent Systems

Agah [2001] presents a research taxonomy for human interactions with intelligent systems, a category which includes robots. Agah differentiates systems according to five categories: application, research approach, system autonomy, interaction distance, and interaction media.

We believe that the research approach does not fit well into a taxonomy for human-robot interaction, as we are concerned only with human-robot systems that have been implemented. Agah's classifications in the research approach category classify the tone of the research paper, rather than the approach of the implemented system (if there is one).

Using the classifications suggested by Agah, interaction media is not particularly relevant to human-robot interaction. He does not address how information is presented to the user via the user interface, instead listing the I/O devices used in a system. Input and output devices are important and must be selected for the end users, but it is much more important to consider how the system

provides decision support in the interface by presenting relevant information.

While application does play a role in the classification of a system, its impact is on the interaction distance and team composition, so we do not include this as a separate category in our taxonomy.

We do include interaction distance and system autonomy in our taxonomy. However, we allow for a finer granularity in system autonomy than Agah, who specifies the categories of “without autonomy” and “with some autonomy.” With interaction distance, we have fewer categories in our taxonomy, choosing to treat the case of an operator and a robot in different locations as one category, instead of including “different rooms/buildings,” “different cities/countries,” “earth/space,” and “earth/subsea.” These categories are concerned with the time lag in interaction, which we handle in our time/space taxonomy category.

Human-Robot vs. Human-Computer Interaction

Scholtz [2002] states that human-robot interaction differs from human-computer interaction in four dimensions, which can be considered categories for a taxonomy of human-robot interaction. The four dimensions are the levels of human interaction, the necessity of environment interaction for mobile robots, the dynamic nature of robots in their tendencies to develop hardware problems, and the environment in which interactions occur.

Scholtz proposes three levels of human interaction that are possible. In the first, supervisory interactions take place between a human and a robot in a remote location. The supervisor needs to know the mission, an overview of the situation, the capabilities of the robot and any problems, and how the robot interacts with other robots (if there are any). Scholtz points out that this interaction level is similar to the HCI domain of complex monitoring devices.

The second level of interaction is peer to peer, where each human and robot contributes to a team according to his/its capabilities. In this situation, the human user will need to know the status of the robot, the robot’s world model, other interactions that are occurring, and the robot’s action capabilities.

The final level of interaction is mechanic, where a user is teleoperating a robot, requiring the user to be a skilled user of the robot. In this level, the user needs to know similar things to the peer to peer level, but must also have information about the robot’s sensors, other jobs that need attention, effects of adjustments on plans and other interactions, and mission overview and timing constraints. This interaction level has several drawbacks, including the need for high bandwidth communication, cognitive fatigue from repetitive tasks and information overload [Murphy and Rogers 1996].

Time-space taxonomy

In accordance with our contention that HRI can be viewed as part of the CSCW field, we examined taxonomies associated with CSCW. The canonical CSCW taxonomy is the so-called “time-space taxonomy” [Ellis et al. 1991]. The time-space taxonomy divides CSCW into four categories based on whether collaborators are using computing systems at the same time (synchronous) or different times (asynchronous), while in the same place (collocated) or in different places (non-collocated). For example, email systems fall into the category of asynchronous and non-collocated, while video teleconferencing systems are primarily synchronous and non-collocated. Computer-assisted crisis management spaces (“war rooms”) can be used in an asynchronous yet collocated manner by teams on different shifts, while electronic meetings rooms are designed to support synchronous and collocated operation during computer-assisted face-to-face meetings.

The time-space taxonomy is applicable to HRI, as we describe below in the taxonomy, because it is useful to be able to talk about whether the humans and robots are working together at the same time or different times, in the same place or in different places.

Collaborative application taxonomy

Another taxonomy of CSCW applications, called a “collaborative application taxonomy” [Nickerson 1997], extends the time-space taxonomy to add a “modal” dimension: the mode of communication used by collaborators. The three modes of communication identified by Nickerson are audio, visual, or document (data); these modes may be used alone or in combination, yielding seven different possible communication approaches. Combined with the four possible time-space categories, there are 28 total categories in the collaborative application taxonomy.

The collaborative application taxonomy does not provide an adequate description of HRI because human-robot and robot-human communication can take forms other than audio, visual, or data (for example, communication can be tactile or haptic). Nickerson’s implicit assertion, that the communication mode used by collaborators is an important characteristic of collaborative systems, nevertheless has merit. In human-robot collaborative systems, communication mode is analogous to be the type or means of control from the human(s) to the robot(s) and the type of sensor data transmitted (or available to be transmitted) from the robot(s) to the human(s). Thus human-to-robot control type and robot-to-human sensor information type are included in our taxonomy below.

Multi-agent robot taxonomy

Taxonomies for systems with multiple robots have also been detailed [Dudek et al. 2002] and [Balch 2002]. Since human-robot teams may contain multiple robots, it is appropriate to examine these taxonomies and their contributions to a taxonomy for human-robot interaction.

Dudek, Jenkin and Milios [2002] point out that the task to be accomplished impacts the organization of a multi-robot team. Some of these tasks require multiple agents, as they can not be completed by a single robot. Other tasks traditionally use multiple agents, but interaction is limited. A third category is traditionally single agent tasks, meaning additional agents do not add to the speed or efficiency of the solution. Finally, there are tasks which could benefit from the use of multiple agents, although they may also be performed by a single agent.

Balch [2002] specifies a taxonomy for the task and reward of a multi-robot group. The task and reward taxonomy is divided into a number of categories: time (how long task is allowed, plus if synchronization is required), criteria for measuring performance (time horizon for optimization), subject of action (robot movement or object movement), resource limits (power, intra-team competition, external competition), group movement, and platform capabilities (task can be performed by a single agent, requires multiple agents, requires dispersed agents, can observe all relevant features of the world, only can get partial information, and requires communication).

Dudek, Jenkin, and Milios also use several dimensions are used for classifying multi-robot systems: group size, communication range, communication topology, communication bandwidth, group reconfigurability, processing ability of each group member, and group composition. This taxonomy differs from Balch by removing the task requirements explicitly from the discussion. Instead, the focus is on the composition, abilities and interactions of the group.

Taxonomy for Human-Robot Interaction

Taxonomy categories, classifications, and examples are described in this section.

Autonomy Level / Amount of Intervention

The amount of intervention required for controlling a robot is part of our taxonomy, because it is one of the defining factors for human-robot interaction. There is a continuum for robot control ranging from teleoperation to full autonomy; the level of human-robot interaction measured by the amount of intervention required varies along this spectrum. Constant interaction is required at the teleoperation level, where a person is remotely controlling a robot. Less interaction is required as the robot has greater autonomy.

In this category, we measure the autonomy level (*AUTONOMY*) and amount of intervention required (*INTERVENTION*). The autonomy level measures the percentage of time that the robot is carrying out its task on its own; the amount of intervention required measures the percentage of time that a human operator must be controlling the robot. These two measures sum to 100%.

Teleoperated robots are fully controlled by a robot operator, usually at a distance. For example, ROBONAUT [Ambrose et al. 2000] is a teleoperated robot that has been developed by NASA. The robot can be controlled either from a spacecraft or from the ground; its operator wears gloves to move the hands of the robot and glasses to see the robot's view of the world.¹ ROBONAUT has *AUTONOMY*=0% and *INTERVENTION*=100%.

At the other end of the spectrum are robots with full autonomy. Examples of this type of control can be found in robots that give tours and delivery robots. Polly [Horswill 1995] gave tours of the 7th floor of MIT's Artificial Intelligence Laboratory. Minerva [Thrun et al. 1999] gave tours of the Smithsonian. Other robots, such as Carmel [Kortenkamp et al. 1993] and Dervish [Nourbakhsh 1998], could navigate indoor spaces and perform delivery tasks. All of these systems used maps of the environment and could localize themselves on the map. At this end of the continuum, the robots have *AUTONOMY* near 100% and *INTERVENTION* near 0%.

In between these two points is a large continuum of robot control, often called shared control. With shared control, the robots are able to do some part of the task and the human operator must do some part of the task. For example, the Wheelesley robotic wheelchair system [Yanco 2000] took over low-level navigation tasks such as path centering and obstacle avoidance in indoor and outdoor environments, while the wheelchair's user was responsible for the high-level directional commands. This wheelchair system would be classified *AUTONOMY*=75% and *INTERVENTION*=25%.

Shared control has traditionally operated at a fixed point, where the predefined robot and operator responsibilities remain the same. However, it is easy to imagine situations where it would be desirable to have a system that could move up or down the autonomy continuum. Human operators may wish to override the robot's decisions, or the robot may need to take over additional control during a loss of communications. Research in this area has been called adjustable autonomy, sliding scale autonomy and mixed initiative. For examples of work in this area, see [Kortenkamp et al. 2002], [Kortenkamp et al. 2000], and [Brummer, Dudenhoffer, and Marble 2002]. Robots that can vary their autonomy levels would have ranges for their *AUTONOMY* and *INTERVENTION* values.

¹ ROBONAUT's researchers are currently investigating the use of some autonomy in the system.

Ratio of people to robots

The ratio of people to robots directly affects the human-robot interaction in a system. This taxonomy classification does not measure the interaction between the operators and the robots, simply the numbers of each. The value of *HUMAN-ROBOT-RATIO* is denoted as a non-reduced fraction, with number of humans over the number of robots. If the number of operators or the number of robots is variable within the system, a range may be specified in either the numerator or denominator of the ratio.

Level of shared interaction among teams

While the ratio of humans to robots is a distinguishing characteristic of a human-robot system, the ratio alone does not provide complete insight regarding the approach to controlling robots. The question needs to be asked: if there are multiple human controllers, are these humans agreeing on commands prior to providing the robot(s) direction, or are they independently issuing commands that robot(s) need to prioritize and/or deconflict? Also, if there are multiple robots, are they each receiving and acting on commands independently, or are all robots receiving all commands and coordinating among themselves to determine which robot(s) should respond to which commands?

Figures 1 through 8 illustrate the various possibilities. A human is depicted by a circle labeled with an “H,” and a robot is illustrated by a circle with an “R.” Double-headed arrows indicate command flows between the humans and robots. In the simplest case, Figure 1 shows one human giving commands to one robot (*one human, one robot*), which sends sensor information back to the human. This case is illustrative of a person operating a wheelchair, or, in the more general HCI world, one person using a word processor program on a single computer.

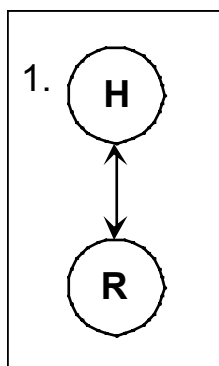


Figure 1. One human controls one robot. Classification value: *one human, one robot*.

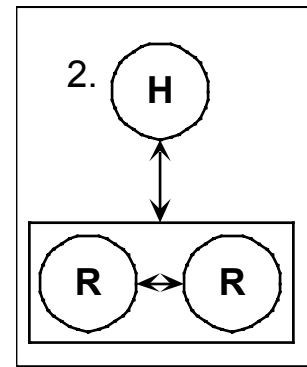


Figure 2. One human controls a group of robots, issuing one command that the robots coordinate among themselves to fulfill. Classification value: *one human, robot team*.

Figures 2 and 3 show one human controlling two robots. (A maximum of two robots and two humans are shown in each figure, but the same concepts hold for “many” as for “two.”) In Figure 2, the human is giving a command to a group of robots that coordinate among themselves to determine which robot(s) should carry out which part(s) of the command (*one human, robot team*). An example of this case is when a person gives a command to a group of robots to clean a room. One robot may vacuum the carpet while another robot may wash the windows. In the complex computing arena, this situation is equivalent to a person starting a program that runs on multiple processors; the program determines which processes will run on which processors.

In contrast to Figure 2, Figure 3 depicts the situation in which one person gives different commands (depicted by a solid arrow versus a dashed arrow) to the different robots (*one human, multiple robots*). The robots do not necessarily need to know what the other robot(s) are doing in order to carry out their tasks. This case may occur in military situations, in which the goal is for one soldier to be able to control multiple robots, each of which may be assigned to destroy a different target. As an example in the CSCW field, one person may be engaging in multiple collaborations with different people using Instant Messenger.

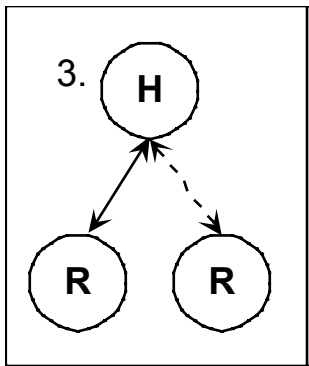


Figure 3. One human controls multiple individual robots, issuing multiple individual commands to robots that operate independently. Classification value: *one human, multiple robots*.

Figures 4 and 5 are the inverse of Figures 2 and 3: multiple people are controlling one robot. In Figure 4, the people coordinate among themselves to issue one command to the robot (*human team, one robot*). An example of this situation is when a firefighter and an emergency medical technician together agree on how a robot should be directed in an attempt to find a victim in a damaged building. A corresponding example in the CSCW field would be when a group of workers use Netmeeting to agree on changes to a Powerpoint briefing before sending it off to a client for review.

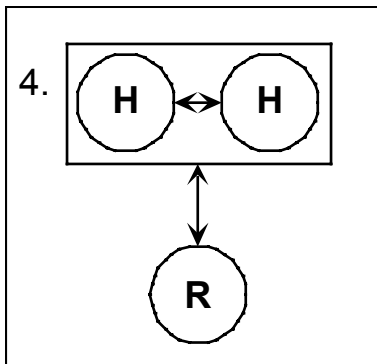


Figure 4. Humans agree on robot commands and issue one coordinated command to a single robot. Classification value: *human team, one robot*.

In Figure 5, the humans act independently, and send different commands (shown as two different types of arrows) to the same robot (*multiple humans, one robot*). The robot must deconflict and/or prioritize the commands before carrying them out. An example of this type of robot is a delivery robot, who is asked to deliver a sandwich to one person and a steak to another. The robot must decide which person's meal should be delivered first, perhaps based on a "first in, first out" scheme. The same type of delivery problem occurs in the web-based computing

world when multiple people place orders with a small web-based company called OnePerson'sBusiness.com.

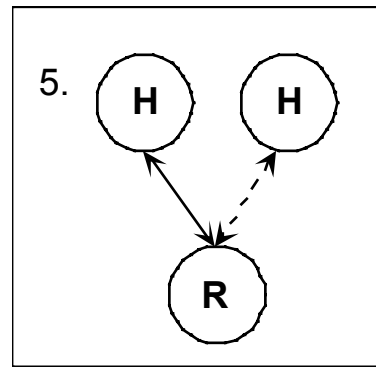


Figure 5. Humans issue different commands to a single robot that the robot must deconflict and/or prioritize. Classification value: *multiple humans, one robot*.

Figures 6 through 8 depict the cases with multiple humans directing multiple robots. Figure 6 illustrates a team of humans directing a team of robots (*human team, robot team*). The humans agree on one command that the robots then coordinate on to decide what robot(s) carry out what part(s) of the command. Such a situation may occur in a search-and-rescue operation that requires multiple robots to carry out tasks. A CSCW example would be when two opposing legal teams hold a computer-assisted videoteleconference to discuss a possible settlement. In this case, both teams had agreed in advance what their bargaining position is with respect to the other team.

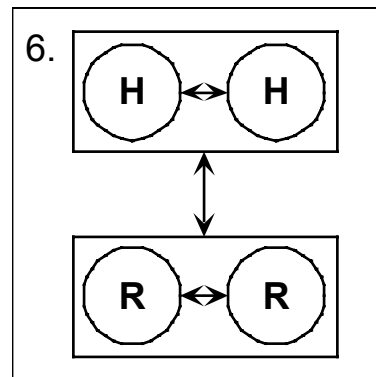


Figure 6. A team of humans issue a command to a team of robots. The robots coordinate to determine which robot(s) performs which portion(s) of the command. Classification value: *human team, robot team*.

In Figure 7, a team of humans issues different commands to different individual robots (*human team, multiple robots*). The humans agree which command

should go to which robot, and each robot acts independently to fulfill the command (thus, no coordination is needed among robots). This situation may occur in the military, if multiple soldiers work together to direct individual robots to each destroy a different target. For a CSCW example, consider a team of people using an electronic meeting room to agree on a series of decisions that are carried out by individuals who are notified of their tasking via separate email messages.

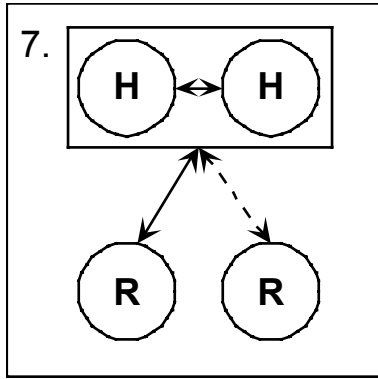


Figure 7. A team of humans issues one command per individual robot. Classification value: *human team, multiple robots*.

Finally, Figure 8 shows the case where individuals do not coordinate prior to issuing different commands to a team of robots (*multiple humans, robot team*). The robots deconflict and/or prioritize the different commands as well as divide the commands among themselves prior to carrying them out. A group of cleaning robots that received instructions from multiple non-coordinating humans would fit in this category. An example in the CSCW field might be when individuals place orders with Amazon.com (which presumably handles orders using a coordinated team).

The taxonomy classification for the level of shared interaction among teams is *INTERACTION*. It can have one of the eight following values: *one human, one robot*; *one human, robot team*; *one human, multiple robots*; *human team, one robot*; *multiple humans, one robot*; *human team, robot team*; *human team, multiple robots*; and *multiple humans, robot team*. We do not include the category of “multiple humans, multiple robots,” as we believe that some coordination must happen at either the human or robot end with multiple agents.

Decision support for operators

When discussing interface design for human-robot interaction, it is most important to consider the type of information that is provided to operators for decision support. This taxonomy category has a few subcategories: available sensor information, sensor information provided, type of sensor fusion, and pre-processing.

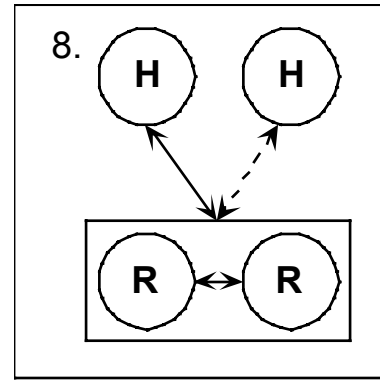


Figure 8. Individual humans issue different commands to a team of robots, which the robots must deconflict and/or prioritize and divide among themselves. Classification value: *multiple humans, robot team*.

The specification of available sensors is a list of sensing types available on the robot platform; the list may also contain the location of the sensors, although this is likely to be too detailed for our requirements. The *AVAILABLE-SENSORS* list is used as a baseline for understanding the values of *PROVIDED-SENSORS*, *SENSOR-FUSION*, and *PRE-PROCESSING*; we will know what was available to the interface designer when he or she selected the sensor information to be conveyed to the operator for decision making.

The sensor information provided, *PROVIDED-SENSORS*, is also a list of sensing types, which is a subset of *AVAILABLE-SENSORS*. All of the available sensor data may not be required for decision support. For example, a robot may use its sonars to navigate, but only a video image is provided in the interface.

The type of sensor fusion, *SENSOR-FUSION*, is specified as a list of functions. For example, if sonar and ladar values were used to build a map that was displayed, the sensor fusion list would contain `{{sonar,ladar}→map}`.

Finally, the amount of pre-processing of sensors for decision support is denoted in the *PRE-PROCESSING* list. If sonar values were used to create and display a map, the list would include `{sonar→map}`. If a video stream is processed prior to display to highlight regions of a particular color, say red, the list would include `{video→highlight red regions}`.

Measuring the use of sensor data in the user interface will allow us to determine how the amount of decision support affects the performance of an operator. It should be easier to control a robot that provides decision support in the form of a map rather than the raw sensor readings from all of the sonar sensors at each reading.

Criticality

While we do not include the application in our taxonomy, we do include a measure of the task's criticality, denoted *CRITICALITY*. Criticality measures the importance of getting the task done correctly in terms of its negative effects should problems occur. For example, if a robotic wheelchair were to

This is a highly subjective measure. To counteract this problem, we define a critical task to be one where a failure affects the life of a human. For example, the failure of a robotic wheelchair to recognize a down staircase could severely injure or kill its user. The failure of a Furby to act properly threatens no one. A hospital delivery robot does have some criticality in its task, since failure to bring a critical sample to the lab in time could be harmful. However, food delivery is a much less critical task, since a late delivery is unlikely to harm a person seriously.

Due to its subjective nature, *CRITICALITY* is broken into three categories: *high*, *medium* and *low*. Urban search and rescue has *CRITICALITY=high*; it is dangerous for its user to be near the disaster situation and it is important to find survivors quickly without damaging the building or hurting a trapped person. Robot soccer has *CRITICALITY=low*; if a robot team fails while playing another robot team, it will simply lose the game. The hospital delivery robot is an example of *CRITICALITY=medium*.

Time/space taxonomy

The time-space taxonomy [Ellis et al. 1991] divides human-robot interaction into four categories based on whether the humans and robots are using computing systems at the same time (synchronous) or different times (asynchronous) and while in the same place (collocated) or in different places (non-collocated).

		Time	
		Same	Different
Space	Same	Robot Wheelchair	Manufacturing robots
	Different	Urban Search and Rescue	Mars Rover

Table 1: Time-space taxonomy category, with examples.

Robots such as the Mars Rover fall into the category of asynchronous and non-collocated because they are largely autonomous and are located remote from their team of human controllers. Rescue robots operate primarily in a synchronous and non-collocated manner as they explore buildings or spaces too dangerous or too small for humans to enter. Robots on the factory floor may occupy the same space (and perhaps perform the same task) as a human

worker doing the same task at a later time. Assistive robots, such as a robotic wheelchair, operate in a synchronous and collocated fashion as they are intended to help a person live better in his or her environment.

The time-space classification is specified in two values: *TIME* and *SPACE*. The possible values for *TIME* are *synchronous* and *asynchronous*. The possible values for *SPACE* are *collocated* and *non-collocated*.

Composition of Robot Teams

Finally, our taxonomy contains a classification for denoting whether robot teams contain different types of robots or the same type of robot, if there is more than one robot in use. Homogeneous teams will lend themselves to a single interface more naturally (although it may need to be repeated for each robot). To present the information from heterogeneous teams, it is likely to be more difficult to present the sensor information from different types of robots in a coherent fashion that supports decision making for each individual robot.

This measure is called *ROBOT-TEAM-COMPOSITION* and can have the values *homogeneous* or *heterogeneous*. *Heterogeneous* may be further specified with a list containing the types of robots in the team and the number of each type of robot used in the team.

Conclusions

Drawing from the fields of HCI and Robotics, this paper presents a taxonomy for human-robot interaction. Using these classifications to define individual HRI systems will allow for the comparison of different HRI approaches in many different categories. The categories and classifications are grounded in real life examples to simplify the classification process.

In addition to setting out a new taxonomy for human-robot interaction, this paper also discusses how work done in the HCI field can inform research and design in the rapidly growing field of human-robot interaction.

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