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A Survey of User Interfaces for Robot Teleoperation

by

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Abstract

Robots are used today to accomplish many tasks in society, be it in industry, at home, or as helping tools on tragic incidents. The human-robot systems currently developed span a broad variety of applications and are typically very different from one another. The interaction techniques designed for each system are also very different, although some effort has been directed in defining common properties and strategies for guiding human-robot interaction (HRI) development.

This work aims to present the state-of-the-art in teleoperation interaction techniques between robots and their users. By presenting potentially useful design models and motivating discussions on topics to which the research community has been paying little attention lately, we also suggest solutions to some of the design and operational problems being faced in this area.

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1 Introduction

Robots are artificial virtual or electro-mechanical agents. As concisely pointed out by Scholtz *et al.* (2004), however, there is no standard definition of what a robot is. They are designed to perform or help perform specific tasks for humans. Similar to humans themselves, they are capable of perceiving their surrounding environment, reasoning about it, and applying some actions to it according to its goals, be the latter human programmed in their memories or not.

Robots can be classified into three groups. The first are industrial robots, which are used in modern manufacturing companies. They generally have very little intelligence and perform specific repetitive tasks with a high level of precision. The second group, service robots, has features that are the opposite of industrial robots. They are more intelligent and perform a set of various tasks that do not require precise results, but yet achieve general goals (Bien *et al.*, 2007). The third group comprises the robots with special missions (Drury et al., 2006; Murphy, 2004; Aubrey et al., 2008; among others). These robots are designed to perform specific tasks. However, differently from industrial robots, the task to be performed is generally very complex. Because of this, these robots require not only a high level of artificial intelligence, but also an operator to guide the robot and help it accomplish these goals. This last group will be the one on which this paper focuses.

These *mission robots* are typically capable of navigating through the environment, as well as making complex physical movements to manipulate objects and affect the state of the environment. Most of the time, however, these robots are not autonomous. If we reduce our scope to electro-mechanical robots, this fact is even more evident. Not only do they require constant maintenance, but also request assistance from a human expert whenever reaching a state of interaction with the perceived environment whose next actions are unknown or indiscernible by its artificial intelligence algorithms.

In order to alleviate the complexity of the real world with which they have to deal, they are designed to accomplish a specific task in a well-defined environment. Even with such constraints, robots more often than not demand human support. On account of this, most mission robots are operated, remotely or locally, by one or more human specialists. However, much like any other tool, robots enhance human capabilities, enabling them to perform tasks that a human alone would not be able to. These advanced tools can perceive more information from the environment by sensing human extra-sensorial data such as radiation, temperature, pressure, humidity and specific gas levels (Yanco *et al.*, 2006). They are also more resistant to human-hazardous environments and to larger ranges of atmospheric conditions, being used for undersea exploration, fire rescue, and duct cleaning (Koh *et al.*, 2001).

The design of a robot is a non-trivial task, requiring knowledge from many areas of engineering, as well as Computer Science, Psychology, and Design, among others. Moreover, the evaluation of the final system, including the robot and the team of humans behind it, is even more difficult to carry out.

Human Robot Interaction (HRI) is the area of research that deals with these kinds of problems. It comprises not only research on remote operation of robots, but also on enhancement of human perception by using these types of machines. It also includes the development of autonomous robot behavior so that robots themselves can perform tasks with as little human interference as possible (Adams *et al.*, 2005; Crandall & Cummings, 2007).

This paper aims to present a review of the state-of-the-art of research in this field, specifically in teleoperated HRI, as well as to provide a general categorization structure. It also proposes a design model and potential experimental solutions for some of the problems in the area. In the next section, an introduction to the common concepts and terms is given. Section 2 identifies the users involved in human-robot interaction. Section 3 describes the technology used in the field. Section 4, the core of this work, provides a description of current HRI techniques and also proposes a model for identifying tasks and requirements built on previous work in the area. Section 5 gives an overview of the common metrics for validation and verification of a human-robot system. Section 6 presents some important HRI research challenges. Last, section 7 gives some conclusions and insights for future work. Some of the terms in *italics* are concepts small enough to not deserve a topic for them, but important enough to not be kept out. A brief explanation of those can be found in the Glossary.

1.1 Definitions

In order to delve into the field of HRI, an understanding of a common set of definitions is of utmost importance. This section highlights core concepts such as telerobotics, situation awareness, telepresence, and immersion, among others.

1.1.1 Task

A task is any activity that a user or operator has to accomplish within an environment through a system interface. It is different from the concept of an *action*. A set of actions in a virtual or remote environment may or may not contribute to the performance of a task.

In the context of teleoperation, a task can divided into four main parts (Parasuraman *et al.*, 2000):

1. Information acquisition: gathering information from the robot and its surrounding environment;
2. Information analysis: understanding what the gathered information means;
3. Decision and action selection: deciding what is the next action the HRI system should perform;
4. Action implementation: performing that action.

The tasks that an HRI system can perform can generally be categorized into a hierarchy of subtasks as in Miller & Parasuraman (2007) to enhance performance and keep workload, the latter explained in section 1.1.6.

1.1.2 Pose

Pose can be defined as the current physical configuration of the robots limbs and joints. As it was presented in the experiments performed by Drury (2006), the pose directly affects the set of tasks a robot can perform, not only because its shape may change, but also because the tools that are available may also differ from one configuration to another.

The complexity in the number of poses of a robot may be measured based on the number of joints and the number of degrees-of-freedom in each join. The higher this number is the greater will be the operator's cognitive load and interaction time. Proper interface design may reduce the effort in understanding this complexity.

1.1.3 Artificial Intelligence

In general terms, artificial intelligence (AI) defines the capacity of a machine to reason about a situation and take action that maximizes its chances of success. This includes such tasks as playing chess well, finding optimal paths between locations, expressing feelings, or driving a vehicle. In HRI, this term is mostly related to the level of autonomy and event recognition of a robot (Adams, 2005; Bien & Lee, 2007; Humphrey, 2008).

1.1.4 Delegation

According to Merrian-Webster dictionary delegation can be defined as: (1) the act of empowering to act for another or (2) a group of persons chosen to represent others. From a teleoperation point-of-view, delegation can be understood as the act of designating tasks to a group of one or more entities, be they humans or not.

Miller & Parasuraman (2007) describe the concept of delegation, also called tasking, task management or dynamic function allocation (DFA) (Calefato *et al.*, 2008), as a real-time division of labor. Its dynamicity contrasts with the concept of application design, where division of labor is done during the creation of a system, a static activity once the system is implemented and running.

Delegation can be ultimately defined as the designation of roles or function in an HRI system. As further described in the next section, delegation can be done manually or autonomously.

1.1.5 Autonomy

In HRI, the level of autonomy or automation of a robot is defined by the frequency of its requests for assistance to an operator in order to perform its tasks (Yanco & Drury, 2002; Zeltzer, 1992).

The levels of autonomy for a robot, also called interaction scheme or autonomy mode (Crandall & Goodrich, 2002), may be defined according to the different operation modes as follows. Sheridan, T., & Parasuraman, R. (2006) among others have created a scale to grade different levels of automation, part of which originated from the Maba-maba list, either not always accepted by the entire community as a good approach to automation design (Dekker & Woods, 2002; Parasuraman, 2006), which has caused . The levels presented here are a simplification these and attempt to categorize the most distinctive levels of automation:

- **Fully controlled:** the operator directly controls each and every action of the robot (Yanco *et al.*, 2004). The latter has therefore no autonomy. This level of autonomy is commonly called teleoperation;
- **Shared control:** both the robot and operator take decisions on how the robot should behave. It can be subdivided into:
  - **Safe teleoperation:** the robot is still being controlled, but can perform some actions on its own to guarantee its survival or success, such as avoiding obstacles unseen or ignored by its operator (Yanco *et al.*, 2006);
  - **Semi-autonomous:** The robot is able to take some decisions and actions on its own, but requires assistance in certain situations (Adams, 2006). Standard shared operation mode is the one used in this case. A common example is the use of way points in navigational tasks (Skubic *et al.*, 2006; Goodrich *et al.*, 2001).;
  - **High-level of autonomy:** the robot is almost completely autonomous, requiring minimal or more abstract user intervention such as in social or service robots (Bien & Lee, 2007). Collaborative tasking mode is how the operation of these types of robots is referred as.
- **Fully autonomous:** the robot is completely autonomous. This case currently only realistically happens for virtual robots, also called *bots*;

The autonomy of a robot may also be categorized according to how the task plan is developed in the system (Kobayashi *et al.*, 2005).

- **Pre-planning:** Before performing a task, the robot is set up with a task plan to be followed. If an event that was not predicted in the plan happens, human intervention occurs;
- **Real-time planning:** robots have goals and change plans in real-time. This generally implies a higher level of robot autonomy. Nevertheless, in this case the robot is also subject to the operator’s intervention when a solution to a certain situation event cannot be handled by the robot itself.

One important point to be set about autonomy is that changing its level may have unpredictable effects on the performance of human as part of an HRI system. The correct design of autonomy is of the utmost importance to make autonomy beneficial for the robot-operator relationship during tasks (Dekker & Hollnagel, 2004; Dekker & Woods, 2002). Many times, automation is only deal with some of the situations faced by the HRI system, and hence becomes useless when an unforeseen situation occurs (Parasuraman & Sheridan, 2000). Autonomy is generally given to highly reliable parts of a system or to parts of the system whose tasks involve low *risk*. Good autonomous systems should enable a conversation between the human and the machine part through which a consensus on the current situation is reached (Miller *et al.*, 2005), which is also defined as the “Horse-Rider paradigm” (Calefato *et al.*, 2008). The performance of such a mixed system should then be measured using results from the two parts in conjunction.

Parasuraman, Galster & Miller (2003), Miller & Parasuraman (2007) explain a delegation system with levels of automation (LOAs) and the relation between workload and unpredictability using unmanned aerial vehicles (UAVs) and the RoboFLag system as example. They point out to research that indicate how High LOAs tend to make operators less aware of what is happening in parts of the task that are automated and how mid-level LOAs produced better results. The authors also define levels of automation separately for each of the four main task parts: information acquisition, information analysis, decision and action selection and action implementation. Hierarchical system for tasking is presented using plays.

Higher levels of automation may also lead to a mismatch between how autonomous, robust and reliable the operator thinks it is and how autonomous, robust and reliable a system actually is (Murphy, 2004). This difference may generate undesirable operator behaviors such as *overreliance* (overtrust, naïve trust), *complacency*. Some measurements for reliability have been proposed (Parasuraman & Sheridan, 2000).

In addition, the more autonomous the higher the level of *reliance* or *trust* of a system should be so that whenever there is an error, *compliance* from the part of the operator occurs without hesitation (Sheridan & Parasuraman, 2006; Moray, 2003). Reliance can be achieved for example by making the system *robust* and providing it with a *transparent* and *affordable* interface (Skubic *et al.*, 2006).

There are different approaches to varying the level of autonomy in an HRI system. One possibility is for the system to be *adaptive* (Miller *et al.*, 2005), that is, it automatically adjusts its level of autonomy based on its current state. Its main purpose is to prevent errors, reduce *out-of-the-loop* performance and maintain the right level of SA and workload (Calefato *et al.*, 2008).

According to Sheridan, T., & Parasuraman, R. (2006), adaptive interfaces can be implemented using five categories of techniques: critical events, operator performance measurement, operator physiological assessment, modeling and hybrid methods combining the previous techniques. Adaptive interfaces generally improve performance speed, flexibility and consistency as well as reduce workload and training time. On the other hand, when poorly designed, they may affect decision making due to their behavioral unpredictability by the part of the operator. Completely adaptive systems may lead to reduced situation awareness, trust (too many false alarms, fault intolerance and system failures), complacency, overreliance, skill degradation (operator looses practice with the system), unbalanced mental workload (problems occurs in bursts whenever autonomy fails), performance degradation (operator interventions and monitoring are more abstract and take longer) and decreased user acceptance (operator looses charge of the situation) (Miller *et al.*, 2005). Adaptive interfaces are further discussed in more detail in section 5.2.

It can also be *adaptable* (Miller *et al.*, 2005), whereby the operator itself decides the level of autonomy of the system. In such a system, the operator has the power to define the last parameters that will mold the autonomous behavior of the HRI system. This approach also has its benefits and disadvantages. For example, generally, it gives operators higher levels of situation awareness, but on the other hand operator workload might be higher and cause a reduction in *task capacity*. An extended definition to adaptable autonomy is that of *adjustable interaction* that highlights that not only the level of autonomy of the system may change, but also its interface through which the operator should interact (Crandall & Goodrich, 2002).

Two important dimensions that affect the autonomy level of a system are *abstraction* and *aggregation* (Parasuraman *et al.*, 2005). The former consists in varying the autonomy complexity or abstraction level of the task to be performed. For example, a task called moveToPoint (x,y) would have a lower level of abstraction than a task collectSpheresCloseBy(Radius). The latter defines how large is the number of robotic agents to which particular tasks is assigned. For example, a task requested for a single robot has a lower level of aggregation than a task delegated for all robots in a team.

Decision on when an autonomous behavior should start or finish is also a decision that can be made autonomously or not (Goodrich et al. 2001). An HRI sub-system is called a *response automation system* when it can initiate itself. When the operator is the one with authority to initiate the autonomous behavior it is called a *task automation system*. Similarly an HRI system is *managed by consent* if it can stop its autonomous behavior and notify the operator when that happens or it is *managed by exception* when the operator is responsible for detecting monitoring the system, detecting exceptions and determining when a behavior should be finalized.

In addition, the autonomy of the robot may be controlled by changing the plan of the robot in different ways (Kobayashi *et al.*, 2005; Amant, 2005):

- **Re-programming the agent:** changing how instructions are interpreted by the agent or the set of instructions the agent accepts.
- **Re-programming the environment:** by leaving objects or markers in the environment, or moving objects, the operator, a team member, or the robot itself may affect the autonomous behavior of any robot present in the modified environment.
- **Re-tasking:** the sequence of activities that a robot is supposed to run is directly changed by the operator. Actions may be removed, altered, or replaced by other actions.

Measuring autonomy

One could come up with a value for the level of autonomy. However, this value could not be used as baseline for comparison of different robot systems due to the variation in tasks and their importance among different HRI systems.

For example, consider a robot with the capability of performing a certain number of tasks N. Each task T_i is given a weight W_i according to its importance to its final robot system goals. When performing a mission, the number of times each task T_i is performed is computed and stored in N_i. For each task, the number of interventions I_i is also stored. After the mission, we have the total number tasks and their total individual number of interventions. For a robot that is autonomous, that is, that can perform one or more tasks and not only respond to the operator input with actions, a value for the level of autonomy L of the robot system could then be estimated by equation 1 below.

$$L = \frac{\sum_{i=1}^{N} \left(\frac{N_i}{\sum_{j=0}^{j=I_i} 1} \right) W_i}{L_{Max}}, \text{where} \quad 0 \le L \le 1 \tag{1}$$

$$\text{where} \quad L_{Max} = \sum_{i=1}^{N} N_i W_i$$

L would represent a measure of autonomy for a certain type of robot system. The closer $|L|$ is to 1, the more robust is the system autonomy. If there is one intervention during a task N_i, its value is decreased to half. If there are two, the value is decreased to a third and so on. It is important to notice however that because W_i are defined subjectively by the robot team or researchers, there is no standard robot tasks weight table that could defined and use as a basis for different research projects. The weights may and, perhaps, should vary according to the importance of their related tasks to the final goal for different robot systems.

1.1.6 Workload

Workload consists of the amount of work that is attributed to each member of a team operating a robot. The workload is directly dependent on the following factors:

- **Intra-Robot autonomy:** The less autonomous a robot is, the higher the operator's workload (Scholtz, 2003).
- **Number of robots being controlled:** as the number of robots to be controlled by the operator increases, workload also does (Humphrey *et al.,* 2008; Parasuraman et al., 2005). Inter-agent autonomy then plays an essential role in reducing workload by allowing robots to work collaboratively. If a team of robots is grouped to work with a certain objective in common, this group is called a *coalition* (Adams, 2006).
- **Interface complexity:** the greater the different types of data that needs to be assimilated by the user, the higher is the *cognitive overhead* and hence the system workload (Johnson *et al.,* 2003; Miller & Parasuraman, 2007);
- **World complexity:** the higher the complexity the world where the robot is immersed the higher the chances of a decreased performance, and possibly higher workload. The complexity of an environment may be measured by entropy estimates (Crandall & Goodrich, 2002).

Among the factors that impact workload are remote world and interface complexity. Hence, it is extremely important that an optimal mapping of these data channels into the operator's sensorial system is performed during system design in order to reduce workload and avoid *incidents* and *accidents*.

In addition, proper distribution of workload amongst team members is essential for the removal of bottlenecks and to increase the global system performance. To understand automation profile of a certain system, Miller & Parasuraman (2007) defined different levels of autonomy for each part of the task that was being performed using the system.

1.1.7 Situation Awareness

One important concept in HRI is one of situation awareness, or *SA* (Endsley, 2000). Situation awareness definition, as well as other definitions such as workload and complacency, and its usefulness as a measuring parameter has been a matter of debate in the community in the last decade (Dekker & Hollnagel, 2004; Dekker & Woods, 2002; Parasuraman & Sheridan, 2000).

In general HRI terms, situation awareness can be defined as how much knowledge of the state of the remote environment and the HRI system the operator has based on the information presented by the HRI system itself. This concept of situation awareness has also been extended for an entire HRI team (Freedman & Adams, 2007) In this, case the SA levels comprises the SA from the autonomous robots plus the SA of each human member.

There are three different levels of SA of the environment:

- **Level 1:** Perception. The operator perceives cues in the environment. That is, being able to notice important information.
- **Level 2:** Comprehension. Integration, storage, and retention of information. This involves not only finding chunks of information, but also making sense of them.
- **Level 3:** Projection. Forecast future situation events and dynamics from the current situation. It allows for timely actions and is a characteristic of an expert user.

Other factors that tend to significantly influence the level of an operator's SA are the following (Gugerty & Tirre, 2000, Bolstad & Hess, 2000):

- **Workload:** Great levels of workload, or its affecting factors, tend to reduce the level of SA (Humphrey *et al.*, 2008). The more assistance a robot requests, the more time will be dedicated to dealing with the robot instead of solving the primary task. The more robots the user has to control, the more attention will be split among them, and the less time the operator will have to answer to each of the robots' requests for assistance. The greater the different types of data that need to be assimilated by the user, the higher the chance that information is missed. Hence, effectively and efficiently mapping these data channels into the operator's sensorial system is of great importance.
- **System factors:** Working memory, perceptual-motor ability, age, and static, dynamic, and temporal processing abilities are properties of the system comprising the entire robot-team and that affect the level of SA from the environment (Endsley, 2000).
- **Environmental factors:** weather, terrain, location, operational requirements are also factors that affect and determine the level of situation awareness of the system (Freedman & Adams, 2007);

SA is directly related to other robot-interaction concepts such as neglection, interaction time and fan out. *Neglection* represents the measure of lack of attention that a robot receives from an operator. It may result from time delays, operator overload, or autonomy. The interaction process may suffer from delays due to either system overload or temporal-spatial limitations. Operator overload results from poor balance between the amount of effort dispended by the operator for each robot, which is defined as *interaction time*, and the number of robots that he is controlling or supporting, defined as *fan out* (Goodrich *et al.*, 2001) and the *switch time* from one robot to another (Goodrich *et al.*, 2005). Another way to defining the relation between the number of humans and robots in a system is by describing its *human-robot ratio* which is, as the name says, the ratio between the number *H* of humans used to use a number *R* of robots (Yanco & Drury, 2002, 2004). So, if there is only one operator for controlling one or more robot, this ration should smaller than or equal to 1.

Parasuraman *et al.* (2008) argues of the importance of concepts such as situation awareness, mental workload and trust in automation in general. These three concepts are very clearly specified and distinguished from other existing constructs such as choice (the ability of choosing), performance (how good the results of a user in a task are) and general knowledge ("long term memory for facts, procedures or mental models").

An HRI interface is composed of many types of information displays that define its various *degrees-of-freedom*. A competent operator assumes an *eutactic behavior*, that is, (s)he knows how frequently each part of the interface must be monitored and for how long (fixation time) in order to obtain optimal results. Researchers on situation awareness have been discussing whether, in order to avoid *complacency* or *skepticism* when monitoring an automated system interface, each part of the interface should be optimally monitored following the Nyquist frequency or perhaps, other approaches such as the use of alarms should be considered (Parasuraman *et al.*, 2008; Moray, 2003; Senders, 1964).

Situation awareness is currently being studied for specific tasks and problems, so that the factors that affect it can be more easily detected. Drury *et al.* (2006) describes in details a decomposition of SA for UAVS based on the group's experience with the military. Freedman & Adams (2007) define inherent components of SA for unmanned vehicles (UV), that is, how hardware and software limits the SA level of the UV system.

1.1.8 Immersion

Immersion can be defined as an objective measurement of the degree of perceptual freedom of a certain reality that a sensorial interface provides to the user (Zanbaka *et al.*, 2005; Bowman *et al.*, 2005). In other words, it is the measure of realistically representing a reality. Immersion is a Virtual Reality concept that can also be applied to HRI interfaces. It can be measured by the quality of display devices and user interaction (Zeltzer, 1992). It is important to underscore that the definition of a *display device* is any device that provides the user with sensorial feedback. Thus, a display may provide any of the five senses with cues.

1.1.9 Presence

Many definitions for presence have been proposed in the Virtual Reality and Tele-robotics communities (Zeltzer, 1992). In general terms, presence is the sensation that the user has of really being in the world that is presented by this system.

A general methodological approach to accurately measure presence for an immersive system is still unknown. However, some of the factors that relate to presence are known, such as the level of immersion of a system. It is also known that presence may positively affect user performance. Three methods are currently in use for measuring presence (Riva *et al.*, 2003):

- **Subjective:** The user is asked about his level of presence;
- **Behavioral:** Presence is measured based on the user behavior while using the system, such as ducking when a virtual object is thrown at the user;
- **Physiological:** Physiological properties of the user's body, such as heart beat rate, skin conductance, and skin temperature, can be monitored while the user is using the system. These factors are then related to the level of presence of the user in the environment.

The HRI community has applied similar measurements to other metrics such as situation awareness (Crandall & Cummings, 2007).

1.1.10 Telerobotics

Telerobotics can be defined as *a direct and continuous human control by the teleoperator* or as a *machine that extends a person's sensing and/or manipulating capability to a location remote from that person* (Sheridan, 1999). It also refers to the area of research dealing with remotely operated robots in any level of complexity.

2 Users

The categorization proposed by Scholtz (2003) encompasses more generally the personnel required in the operation of a robot.

The *supervisor* is a person who monitors and controls the overall situation. He is responsible for evaluating the actions based on the perception of the system and ensuring that these actions will lead to the achievement of higher-level goals. That is, when performing a task they ask themselves how, when, and with what resources it should be done (Miller & Parasuraman (2007). For automated robots, the operator assumes the role of the supervisor, being responsible for: planning off-line, teaching and monitoring the robots, executing a plan and intervening to abort or assume control as necessary and learn from experience.

The *operator*'s role is to ensure the robot is acting as expected. Whenever the robot is unable to autonomously deal with a certain situation in the environment, the operator intervenes to take the right action. This intervention may be expressed as a simple change in the parameters of the robot's AI scripts, or directly manipulating its steering and pose. From a supervisor's point-of-view, an operator is the ultimate human-friendly interface to the limited or low-level robot interface.

A *mechanic* assists in the resolution of hardware and software issues that cannot be resolved by the operator. This implies remotely fixing low-level software problems, hardware monitoring, and physically replacing electronic and mechanical parts *in locu*.

The *bystander* plays an important role in robot experimentation. His job is to affect the robot actions by directly interacting with it in the remote environment. They are useful to study people's reaction when having to socially interact with an advanced machine such as a robot.

The last type of user is the *team mate*. These are other supervisors and operators that are controlling other robots, or other parts of the same robot. Additionally, robots maybe part of a team of humans and cooperate in a shared environment, such as in a space mission (Atherton *et al.*, 2006).

For some tasks, such as USAR, HRI teams are coordinated by *managers* and *leaders*. Even though this type of personnel is not directly in contact with the robot, they constantly communicate with the robot teams, access relevant robot data, coordinate the activities of the many HRI teams and decide the *feasibility* of certain activities or the course of the mission as a role (Murphy, 2004; Casper *et al.*, 2000; Osuka *et al.*, 2002).

2.1 Teams

Reasoning from the above user descriptions, it is clear that a team is a multi-disciplinary, highly specialized group of people, whose sole objective is to guarantee the success of a human-robot mission. The use of teams is not only a solution for aggregating different levels of expertise, but also for reducing the cognitive load for individual users, which leads to a reduction in their change of focus among different task and an increase in their SA individually and as group. But ensuring information communication and consistence amongst team members is not a trivial task (Murphy, 2004).

A mission, however, may be shared by one or more teams. This is particularly true in rescue and military missions, when large geographical areas must be covered. On the other hand, it is possible to have different teams, each with different objectives and robot capabilities, who collaborate as a coalition to accomplish a higher-level goal or a complex task (Adams, 2006). An operator then assumes the role of a supervisor or delegator by managing the robot statuses and controlling teamwork performance (Miller & Parasuraman, 2007). Common tasks accomplished by humans in a human-robot team (HRT) are: mission (re)planning, robot path (re)planning, robot monitoring, sensor analysis and scanning and target designation (Crandall & Cummings, 2007).

In some cases, different types of robot are involved in a task. *Marsupial robots*, for example, are larger robots whose main role so protect and carry other smaller robots to task areas (Murphy, 2004). Once a desired location is reached, the smaller robots are released to perform their tasks (Osuka *et al.*, 2002).

There are many trade-offs when one decides to increase the level of autonomy of an HRI for it may imply in increasing unpredictable behavior and harder to identify statuses if a good interface is not provided. The more autonomous, the more training and understanding of the system is required for the operator to achieve competency with the system. Since situation awareness becomes more cognitively costly for the operator as autonomy increases, the latter also leads to more stress to the operator. Depending on the task that is being done, environmental stressors and fatigue levels may definitely affect the performance of the team as whole, not only from human, but also from a robotic perspective (Miller & Parasuraman, 2007; Murphy, 2004; Freedman & Adams, 2007).

Interaction between users inside or among teams is therefore crucial to the achievement of a goal. This is typically done by audio communication and from the mutual perception of the situation from different abstraction levels through the robot interface. Etiquette rules are recommended to be established in order to guarantee that communication happens objectively, concisely and unambiguously (Sheridan & Parasuraman, 2006).

Few research groups were found to be working with a single robot and multiple operators (Murphy, 2004, Osuka *et al.*, 2002; Yanco *et al.*, 2004 and others). Most of the current research on cognitive load presents experiments where a single user has control over a set of robots (Goodrich *et al.*, 2001 and others). The robots may then be organized in coalitions (Adams, 2006). But reducing the human-robot ratio may not be possible for all cases. When having one supervisor control more than one robot, Parasuraman *et al.* (2005) reported the following issues in their experiment: uncalibrated trust, mode error, reduced situation awareness, loss of operator skill, unbalanced mental workload. Most of these can be associated with the constant switch among different robots situations (Goodrich et al., 2005; Burke *et al.*, 2004). It is important to carefully know when reducing the amount personnel working with a robot will bring any benefit to the team in terms of cost-performance in long term.

Casper & Murphy (2002) have reported that for USAR tasks, an operator could not do perform as well without a supervisor, due to the workload required in controlling the robot itself and performing a search task. In addition, this same study pointed out the necessity of communication among team members, so that a supervisor is aware of relevant information about the robot and the operator knows what task and actions he is supposed to accomplish with the robot. It is important to notice that switching form what task to another increases the cognitive overhead of the system, since operator needs to adjust its mindset for a different situation when moving between tasks (Goodrich *et al.*, 2005).

The level of cognitive load is then measured for robot sets of different sizes and for different tasks that are to be performed. It would be interesting, however, to have experiments where a single, multi-task robot would be controlled by a set of operators. Then, the complexity of tasks and the number of operators would vary, and some system metrics could be applied for each possible case.

It is our view that, for most situations, robots are not yet autonomous enough to have a set of them controlled by a single user. Having one user control multiple robots must be justified by experimental results proving that an increase in the number of operators would not improve the performance of the system. Robots are still very expensive, and it may be more cost-effective to have a single, less expensive robot controlled by multiple operators that performs better than a large set of expensive robots controlled by a smaller set of operators that performs poorly. Multiple minds may work better in practical terms until robot autonomy is more-fully developed.

Moreover, robot autonomy should be benchmarked against an optimal sized group of operators using an optimal number of robots. Only under these conditions can robot autonomy prove its benefit and advantage over any other possible human-robot configuration.

Figure 1 presents the possible relations between the number of robots and the number of operators. The same relation is also derived between both operators and robots and the number of tasks they may perform. The refinement and optimal matching between the number of operators, number of robots, and number of tasks is a non-trivial problem that requires the attention from researchers with a great deal of experience and knowledge in human-robot interaction. In addition to this, as described in Yanco & Drury taxonomy (2004), there might be collaboration among humans and among robots to accomplish a certain task.

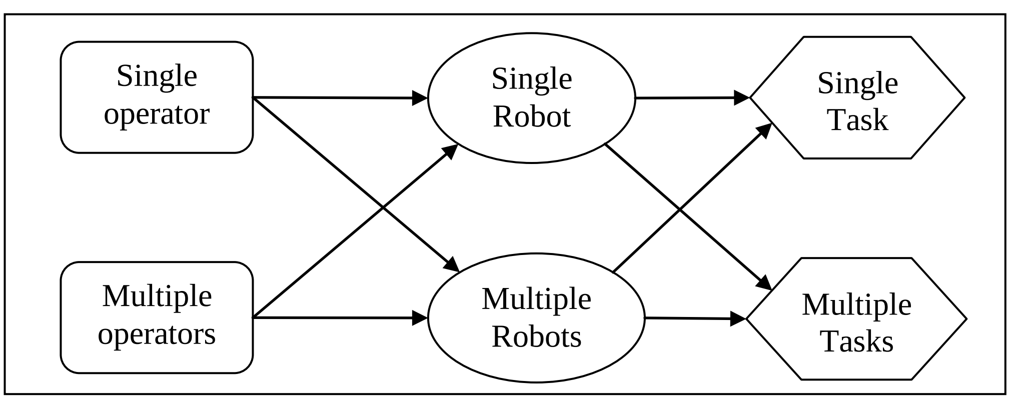

Figure 1: potential configurations between operators, robots and tasks.

2.2 Levels of presence

While the operator is directly controlling the robot, the robot output is shared among all of the users. Hence, the sense of presence from the point-of-view of each one of the users must have measuring parameters conforming to their role. The most common methods for measuring presence were already presented in section 1.1.9. However, since presence measurement is currently still a topic of prolific research even in general terms, measuring presence for each of the specific categories of users in the HRI domain is an open topic.

3 HRI Technology

As previously discussed, the design of technology used in HRI is mostly directed by three types of users: operators, supervisors, and mechanics. Although there are systems to assist in the interaction with bystanders, such as the ones capable of recognizing gestures or expressions, in practice this higher level of processing is typically done by the operator and/or supervisor themselves.

On account of this, the technology presented here is directed to these three types of users and is divided into four categories:

- **Sensors:** Devices that capture information from the system and the environment;
- **Input:** Hardware and software interfaces that collect and process information to be transmitted to other users or converted into actions by the robot in the environment;
- **Displays:** Hardware and software that process and present the processed information from sensors to the users.
- **Actuators:** Hardware that enables the robot to interact and affect the environment.

3.1 Sensors

Error! Reference source not found. lists the most common types of sensors used in HRI systems. They are categorized in terms of their potential functionality and user type. The most common robot sensors are the ones that provide more flexibility in terms of their use. These generally include visual, audio, and spatial sensors. Notice the prevalence of visual feedback in obtaining information from the environment when looking at the functionality column.

Another way of categorizing sensors is according to how they perceive the environment:

- **Radiation sensors:** these include electromagnetic and sound waves. Radiation based sensing, with the exception of acoustic radiation were all grouped as visual sensors. This includes radiation sensors, which emits not only photons but also heavier particles. Most radiation cannot be perceived by the human eye, so most light has to be sensed not form video, but from special-purpose sensors that map invisible light to the human-visible range. Similarly, special microphones and ultrasonic devices are used to detect sounds in the environment and produced by the robot. Due to the bouncing properties of radiation, ultrasonic, laser and infrared devices are used to acquire topological information from the environment.
- **Physical properties sensors:** sensors that detect variation in a force field such as electromagnetic, electrostatic or gravitational. These include mainly proximity and spatial sensors. They can also detect variation in temperature or pressure, generally from the atmosphere.
- **Movement sensors:** these work on detecting how much movement is applied to the sensor itself. They include spatial and haptic sensors.

- **Chemical sensors:** these are sensors that measure the molecular and atomic characteristics of the environment, be its atmosphere or soil. Olfactory and atmospheric sensors are included in here. They are most commonly used to detect There are also organic detectors used for space missions, such as Urey (Aubrey *et al.*, 2008) but they are far from being a commonly used sensor down here on Earth.
- **Mechanical sensors:** they are triggered by abrupt interaction with them. Most analog and digital input devices could be understood as mechanical sensors. Other examples are collision and pose detection sensors.

Table 1: Sensor types used in HRI.

Sensor type	Functionality	Used by	Hardware
Visual	- 2D Camera feed analysis; - 3D perception of the environment; - Visual extra-human perception (infrared, radiation, spectrum filtering); - Atmospheric analysis; - Structural analysis (E.g.: void spaces location in USAR);	Operators, supervisors, mechanics.	- Cameras - Light emitters (flash lights, laser diodes, lasers, infrareds) and receivers (photoelectric sensors, etc.)
Haptic	- Detect collision, vibration, tilt sensing;	Operators	- Collision sensors, - Force sensing resistors (FSRs), contact sensors.
Proximity	- Collision avoidance; - Fall avoidance;	Operators	- Capacitive proximity sensors; - photo-electric sensors.
Atmospheric	- Detect humidity, temperature and pressure.	Operators, supervisors, mechanics.	- Humidity, temperature, pressure.
Olfactory	- Atmospheric analysis and specific gases detection, such as CO2	Supervisors, operators	- Chemical sensors.
Audio	- Perceive sound or noise in the environment or in the robot. - Structural analysis	Operators, supervisors, Mechanics.	- (Directional) microphones - Ultrasonic emitters and receivers
Spatial sensors	- Detect location and orientation of robot and objects to be tracked.	Operators, supervisors.	- GPS systems, accelerometers, gyroscopes, inertia measurement units (IMUs).

3.2 Input

The table below lists the important input devices that are used in HRI. They range from simple PC devices to more advance virtual-reality and application-specific ones. Table 2 describes them in terms of potential applicability and user category.

Table 2: Input device types used in HRI.

Device	Input Capabilities	Applicability	Used by
Keyboard	- Sequential character input	- Symbolic input; - GUI interface control; - General parameter control;	Operators, supervisors, mechanics.
Mouse	- 2 DOF input - Binary input	- GUI interface control; - General parameter control;	Operators, supervisors, mechanics.
Joystick	- 2 DOF input	- Robot navigation; - Camera and sensor control;	Operators.
Touchscreen	- Binary input	- GUI interface control; - General parameter control;	Operators, supervisors.
Tablet displays	- Binary input - 2 DOF input	- GUI interfaces control; - Camera and sensor control; - Robot navigation;	Operators, supervisors.
Audio input	- Analog input	- Speech recognition; - Voice recognition; - Command issuing; - Team coordination.	Operators, supervisors.
Motion tracking	- 2, 3 or 6DOF input;	- Data monitoring and search; - Robot control; - Interface interaction; - Remote world actuation.	Operator, supervisors.

When it comes to GUI control, most input devices must rely on an application-specific layer of software that abstracts the data that is sent to the robot and reduce the cognitive overload of the users. Although extensively used in VR research, other input devices, such as motion trackers are not yet being widely used in HRI. The reason might be for the cumbersome set up and lack of mobility inherent in most of the devices.

3.3 Displays

Displays are used to present data about the status of the robot. These devices are used to either provide the user with a global view of the mission, robots, and other team operation, to give the user feedback on specific actions when interacting with the robot, or to help the user monitor the internal status of the robot, be it in terms of hardware or software.

Many interfaces can be used to improve the display of information. They are generally categorized into three groups: audio, visual and data (Yanco & Drury, 2004), the latter encompassing interfaces for the remaining three human senses which are not so often used. However, much like with input interfaces, data is generally mapped to the visual domain as an abstraction on the GUI interface. Due to the tendency of humans to be more sensitive to visual information than information provided by other senses, this approach tends to be an effective one. A relevant example is the Sensory EgoSphere (SES) created by Johnson *et al.* (2003). The Human Computer Interaction Institute at

Carnegie Mellon University together with NASA has also been working on improving Mars robots interface by using a more usable interface that allows *in-situ* re-tasking (Kobayashi *et al.*, 2005). Nevertheless, the provision of large amounts of visual data leads to cognitive overload on the part of the user and therefore, a decrease in productivity. Different robot perspectives have also been used to improve the amount and organization of visual information on screen (Atherton *et al.*, 2006; Cooper & Goodrich, 2008; Nielsen *et al.*, 2007; Nielsen & Goodrich, 2006;). They represent similar camera models that are used in virtual environments (Bowman *et al.*, 2005):

- **First-person view:** on or multiple camera views are directly presented on screen. Some other information such as sensors statuses and robot pose are presented laterally (Drury *et al.*, 2006).
- **Third-person view:** the camera follows the avatar from the back slightly above it, but always pointing to it, in a backward perspective direction and pointing diagonally towards the ground. In some cases, the angle formed by camera, robot and the projection of the camera position to ground can be adjusted (Nielsen & Goodrich, 2006).
- **Map, God-like or bird's-eye view:** a top-to-ground view of the robot in on top of the map of the location he is traversing (Drury *et al.*, 2003). There are two types of approaching of representing orientation in this type of view.
    - *Robot-up or egocentric:* whenever the robot turns, the orientation of the robot on top the map remains the same and the map rotates, hence always maintaining the forward direction of the robot pointing to the top of the screen;
    - *North-up or geocentric:* when the robot turns, the orientation of the robot changes and the map orientation remains static, hence maintaining north orientation always pointing to the top of the screen;

The use of more senses other than vision to reduce such an overload is increasing, however. Zelek & Asmar (2003) have proposed using a tactile device previously used by the vision-impaired community as a new interface for a robot-operator. A similar approach was taken by Calhoun *et al.* (2003), where vibrating tactors were attached to the wrists of the operator. A tactor is a vibration motor similar to the ones used in mobile phones that not only alert the user about incoming calls and messages, but can be used more generically as a medium for outputting relevant information to the user or operator. Lindeman *et al.* (2003, 2006) has presented important results of the benefits of vibro-tactile displays by experimenting with them on the hips, back, and thorax of the user. Tactors are used in uni-dimensional or bi-dimensional configurations. Other types of haptic feedback displays have been proposed in the area of Virtual Reality. A review of those is presented by Zelek & Asmar (2003).

Table 3 gives an overview of the types of displays used in HRI. Notice the difference in range of the displays compared to sensors. It confirms the fact that most data is mapped as video information to users.

The table also presents other devices (marked with an asterisk) that are currently used in VR research and that could also be applied to HRI interfaces. Notice that there is a great difference between the set of devices available to VR applications (Bowman *et al.*, 2005) and the ones available for HRI.

Table 3: Display devices used in HRI.

Type	Hardware	Output capabilities	Potential Applicability in HRI
Visual	- LCD / CRT displays - Head-mounted displays, caves, and other stereoscopic video-display devices*	- Stereo and mono display of visual information	- General camera feed display, processed image and human vision; - Thermal imaging and infrared data; - Ultra-violet data; - Sonar / ultrasound data; - Any other sensors data; - Overall/map mission view; - Mission flow diagrams.
Auditory	- Speakers - Headphones	- Surround, stereo and mono display of aural information	- Environment sound captured by robot; - Inter-team communication; - Sensor data monitoring.
Haptic	- Vibro-tactors (1D and 2D arrays) - Joysticks with force-feedback* - Phantom* - Novint Falcon* - Gloves and exoskeletons*	- Localized 3D spatial haptic feedback	- Information alerts; - Directional cueing; - Environment information and feedback.
Olfactory	- Air cannons [Yanagida *et al.*, 2004]*	- Display of subsets of smells	- Atmospheric information

3.4 Actuators

Actuators define the HRI technology used to physically interact with the environment. However, if we expand this concept to broader terms and consider actuators as any technology that affects the state of the environment. In that sense, actuators may change the environment they are immersed in different levels. The robot per se is an actuator, since its simple presence may influence the environment it is immersed in.

In a similar manner, the sensors, input and display technology listed above could be used, purposely or not, to change the robot's surroundings. Light emitting sensors may change the state of the environment by the mere fact that they are shedding light on it.

From another perspective, display and input devices, generally used on the operator side, could be used on the robot side to enhance communication between robots and bystanders, hence, empowering the robot as a remote vehicle with more tools for social interaction and human behavioral change. Therefore, bear in mind that most technology already described in the above sections could be used as an actuator on the robot side of an HRI system.

The list below consists of the actuators that have not already been listed in the previous tables, the ones that are commonly classified as actuators. Additionally, some of these actuators can themselves serve as input devices. For example, based on the current state of the joints of a robot arm, the robot pose can be inferred in much like the way haptic sensors is capable of capturing operator input.

Table 4: Simple categorization of types of actuators.

Actuator type	Functionality	Used by	Hardware
Electric motors	- Locomotion; - Movement; Grabbing & moving objects; Pose control;	Operators	- Robotic joints (rotary, prismatic); - Stepper motors; - Linear motors; - Etc.
Artificial muscles	- Precise limb movement.		- Collision sensors, - Force sensing resistors (FSRs), contact sensors.
Pneumatic	- Used in industry for diverse purposes, but not used for mobile robotics.		- Capacitive proximity sensors; - photo-electric sensors. - Humidity, temperature, pressure.
Hydraulic			
Shape memory alloys	- Small movements.		- Artificial muscles
Electro-active Polymers (EAPs)	- Biological muscle behavior emulation.		

4 HRI Techniques

A mission-specific HRI system consists of a selection of a set of technologies and methodologies combined to solve a problem in a specific domain. The reason for the use of a robot is generally because it would be either more costly or dangerous to replace the robot with a human. In addition, when the level of specialization or knowledge to perform a certain task is too high and there are no specialists available locally, robots are used as a communication channel between the environment and a remote specialist. An example of this is the performance of remote surgeries.

In every case that a robot is used, the accompanying HRI system is required to have the following set of features:

- A set of sensors to capture data from the environment where the robot is;
- Display devices that present processed data information to the user;
- A set of input devices to give the operator control over the robot;
- A processing unit to convert data from the user to the robot and vice-versa.

Human-robot interaction techniques therefore relate to one or more of the pertained features of the HRI system. This section groups many HRI techniques according these four important features. It also provides information on what kind of tasks are performed by a robot, how they are performed, and explains potential areas of research and application of HRI.

4.1 Display Techniques

This section describes the set of methodologies, algorithms and hardware configurations that have been used to build HRI interfaces.

4.1.1 Visual

Visual techniques generally include the use of a LCD or CRT monitor to display information to the user. What and how information is displayed, however, varies for each application. Nevertheless, some common techniques exist, such as the ones for 3D mapping that are presented next.

3D mapping is the discovery of the positions of objects in 3D space by analyzing different types of data from the environment. Such data may be the output of sonar, cameras, or photoelectric sensors, for example. Each system has its own way of processing data (Johnson *et al.,* 2003; Nielsen *et al.*, 2007; Yanco *et al.*, 2006), but there are well-known and more widely used techniques, which are characterized here (Zelek & Asmar, 2003):

- **Optical flow**: This consists of the deduction of the speed and direction of movement based on a sequence of images;
- **Stereo vision**: By having a set of two synchronized cameras pointing to the same direction, but slightly displaced horizontally, and capturing data from the environment, it is possible to make a 3D representation of the environment as if it was seen by the human eye;

- **Probabilistic Vision**: This term encompasses a set of techniques to detect objects in motion in a scene based on probabilistic models such as the one derived by the multi-hypothesis tracker algorithm.

4.1.2 Tactile Feedback Techniques

Tactile feedback has been used in HRI as an experimental interface as an outlet for cognitive overload. As summarized by Lindeman (2003, 2006) and Zelek & Asmar (2003), tactile cues have been used as display devices on different parts of the body such as: forehead, tongue, palms, wrist, elbows, chest, abdomen, back, thighs, knees, and foot sole.

Nevertheless, when designing a haptic interface, it is important to consider the fact that human tactual perception sensitivity varies according to body location. Sensitivity on the fingers, lips, and tongue is much higher than on the back and shins, for example, and may affect the user's SA of the remote environment.

Lindeman (2003) provided a classification of the types of contact that can be potentially represented by vibro-tactile display in virtual environments. For tele-operated robots, this classification is applicable without further modifications if we replace the virtual environment with the real remote one. *Impulse contacts* refers to contact within short periods of time while *continuous contacts* refers to situations where contact is maintained for a longer period of time. The latter may be further divided into *sliding contacts*, which are used to represent object surface constraints and physical features, and *pushing and pulling contact* by which the objects weight, deformability, and movement constraints can be represented.

Nevertheless, the use of vibro-tactors to represent surface properties such as friction and texture may not provide the user with the accuracy and fidelity required. Since tactors are designed and arranged for specific application, portability has been an issue in the area. The Tactaid and Optacon, as summarized by Zelek & Asmar (2003), are two exceptions of this.

Based on the work of Lindeman (2003), the set of parameters that could be directly mapped to output data from the robot or the environment are:

- Intensity with which a tactor vibrates;
- The frequency of vibration;
- The duration of vibration;
- Sequence of different or congruent vibrations interspersed by non-vibratory periods; and
- Spatial arrangement of tactors.

These parameters are summarized in **Error! Reference source not found.** and are accompanied by suggestions on which type of sensor data they could represent. These mapping are intuitive propositions that have not been currently validated. It is important, however, to clarify the meaning of the terms *analog display*, which refer to a device that may present to the user a continuous range of values, and *symbolic output*, which presents to the users with codes or symbols that he may recognize or associate with some idea.

Table 5: Vibro-tactile parameters and suggested mappings

Tactor configuration parameters	Suggested outputs
Intensity	Analog display
Frequency	Analog display
Vibration duration	Symbolic output or analog display
Sequence of different or congruent vibrations interspersed by non-vibration periods	Symbolic output or analog display
Spatial arrangement	Symbolic output or analog display

4.2 Input Techniques

Input techniques vary according to the type of user, the type of robot, and the goals of the application. In terms of level of action, a robot may receive input and represent it in the exactly the same way as the movement of the users body, called *direct mapping*, or map it to some other type of movement or control as an *indirect mapping*. An example of direct mapping would be using the movement of the arm of an operator to control a robotic arm. An example of indirect mapping is using a joystick to control how fast robot wheels will turn.

Input is also used for system control, such as setting up the robot's control parameters and algorithms before it is used for manipulation and control. This may be done manually, by running scripts, or by loading configuration files.

Most of the times robot input implies working in imperative mode, but robots with some reasoning exist and can learn from bystanders nearby or team members. Conversations with robots may also take place over the Internet with on-line bots. In addition, computer vision and AI may serve as filters for the robot, deciding on what it should consider as valid or relevant input.

Ideally, the concept of input could be further extended to consider as input also the interaction of the mechanic as input for the robot. Charging the robots battery or tightening his nuts and bolts should also in the future be used as input for robot AI to create laces of human-machine social bonding and thus creating a more realistic interaction between both. There is still a long path in AI before this to become a reality though.

Furthermore, the change in the behavior of the robot may also be achieved by modifying the environment in which it is immersed, such as moving objects or leaving recognizable tags on visible places. Human or robot team workers could leave marks in the environment that will serve as input to the robot , using spray for example, and define what is the situation of an area and what the robot is suppose to do, much like what is done among HRI teams during USAR tasks in collapsed buildings (Murphy, 2004).

Data input from the user may also be interpreted in different ways. The same stream of analog values may be interpreted as a sequence of position values, speed values, or acceleration values, for example. They may also be interpreted as absolute values, or values relative to the current or last value received.

4.2.1 Operability

Operability may be categorized in terms of locality. A robot may be operated locally where the user and the robot are in the same location, or remotely, where the user and robot are in adjacent rooms and the user indirectly operates the robot, such as the many robot arms in laboratories and factories around the world.

It may also be operated remotely, where user and robot are geographically apart from each other. An example of such is the use of the U.S. Army Experimental Unmanned Robot (XUV) for simulated reconnaissance surveillance and target acquisition (RSTA) used by Hill & Bodt (2007) to measure operator workload.

4.3 Human-robot Tasks and Requirements

As mentioned by Miller & Parasuraman (2007) human-robot tasks have already been categorized and classified using various HCI models, such as GOMS, Plan-Goal graphs, PERT, Critical Path Method charts, Petri Nets, Hierarchical task network planner, CIRCA among others. Requirements for HRI systems have also been emphasized of a result of data collected during robot competitions (Yanco *et al.*, 2004; Osuka *et al.*, 2002). However, as Scholtz (2002) well remarked, HRI differs from HCI for having complex control systems, autonomy and it has to deal operate in a real-environment that might be always changing in a fairly unpredictable manner.

Yanco & Drury (2004) have devised their own taxonomy as well as mentioned previously existing ones. A summary of the categories considered are presented in Table 6.

Table 6: Different taxonomies for HRI.

Yanco & Drury	**Task & reward**	**Multi-robot systems**
– Task type: USAR, HAZMAT, etc. – task criticality: low, medium, high. – robot morphology: anthropomorphic, zoomorphic, functional; – ratio of people to robots; – composition of robot teams: homogeneous, heterogeneous; – level of shared interaction among teams; – interaction roles: supervisor, operator, etc. – type of human-robot physical proximity: avoiding, passing, following, approaching, touching – decision support for operators: available sensor information, sensor information provided, type of sensor fusion, pre-processing; – time/space: robot and human using the HRI system at the same time /location or not; – autonomy level/amount of intervention.	– Time: how long it takes and if there is synchronization; – Criteria for measuring performance; – Subject of action: robot/object movement; – Resource limits: power, intra-team/external competition; – Group movement; – Platform capabilities: team organization (one/multiple operator(s) with multiple agents dispersed or in coalition), relevant world feature capabilities, communication requirements.	– Communication range; – Communication topology; – Group size; – Communication bandwidth; – Group reconfigurability; – Processing ability of each group member; – Group composition.

Below is a list of the common tasks human-robots systems are requested to perform. They are divided in higher level tasks and lower level-tasks. Higher level tasks are built upon the lower level tasks. Task from both levels may or may not be autonomously performed. Yanco *et al.,* (2004) has proposed a classification of HRI for mission robots tasks adapted from the HCI NGOMSL model. It divides tasks into high-level and lower level tasks. This model is going to be used here to categorize the most common HRI tasks.

However, here an enhanced model based on Yanco's model is proposed. This model, henceforth called the *HRI Cyber-human Requirement Model* (CHuRM), contains two other layers, each with two other classes of tasks. The idea is to distinguish requirements from their tasks and also to separate both of these into classes that are general to the system, human-related and robot-related. The six types of tasks are presented in Table 7 and in Figure 2. Notice that some of the requirements or tasks may not be necessary depending on the HRI system's goals. Moreover, the tasks and requirements are very focused on the role of the operator. Nevertheless, it could be extended to comprise other users, as described in more detail ahead.

Table 7: CHuRM divides tasks and requirements into three categories: human-related, robot-related and HRI-system-related. Here are a sample of potential tasks divided into these categroies

Task/requirement Type	Examples of tasks/ requirement
HR - Human requirements	- Being aware of the communicative, functional, behavioral potential and limitation: - Graphical user interface (GUI); - Robot; - Team members. - Being physically and cognitively capable of making full use of the three above resources to effectively and efficiently accomplish higher level goals.
HT - Human tasks	- Interpret output values received by human-senses being used in the interface: - Symbolic values; - Spatial values; - Intensity values. - Objects recognition; - Externalizing actions to - Computer and robot input interface through coordinated body movement and gesture; - Human peers through linguistic symbols and body expression. - Event comprehension and prediction.
SR - Human-robot/system requirements (Yanco *et al*'s high level tasks)	- Navigate and monitor the environment; - Search for objects and people - Monitoring the system, including operator and robot, or external factors such as vehicles, moving objects, a person, other robots and human team members; - Measure, interpret and predict the behavior of data that is collected from sensors that are directly available or that are pre-processed; - Robot logistics, such as undocking smaller robots out of a larger one; - Dealing with system failures.
ST - Human-robot/system tasks (Yanco *et al*'s primitive tasks)	- Teleoperation: - Touch objects; - Deviate from objects; - Collect objects; - Move objects; - Monitoring: - Local and remote internal system status; - Local and remote external environment. - User interface manipulation; - Team interaction and idea exchange (CSCW).
RR - Robot requirements	- Include a high-level of autonomy (navigation, collision avoidance, object collection); - Process data to make it cognitively unburdening for the operator; - Understand external environment situations (floor firmness indicates risk of collapsing, high temperature nearby may damage robot); - Suggest action to user (reconsider entering room with uncertain structure stability or in flames).
RT - Robot tasks	- Collect sensor data; - Map sensors state with potential remote environment situations or events; - Associate remote environment situations/ events with potential favorable actions.

The high level layers are used to identify more abstract tasks that here are reinterpreted as requirements. The lower level represents tasks that relate to these requirements. It is important to notice the transition from robot-computer dependent tasks to human skill requirements.

The idea behind the addition of these layers is to highlight the importance of other factors in HRI that affect SA and performance. The original model does not consider the human factors as much as the computer-robot factors, that is, system factors. Moreover, it is relevant to separate the purely human factors from the purely robotic ones.

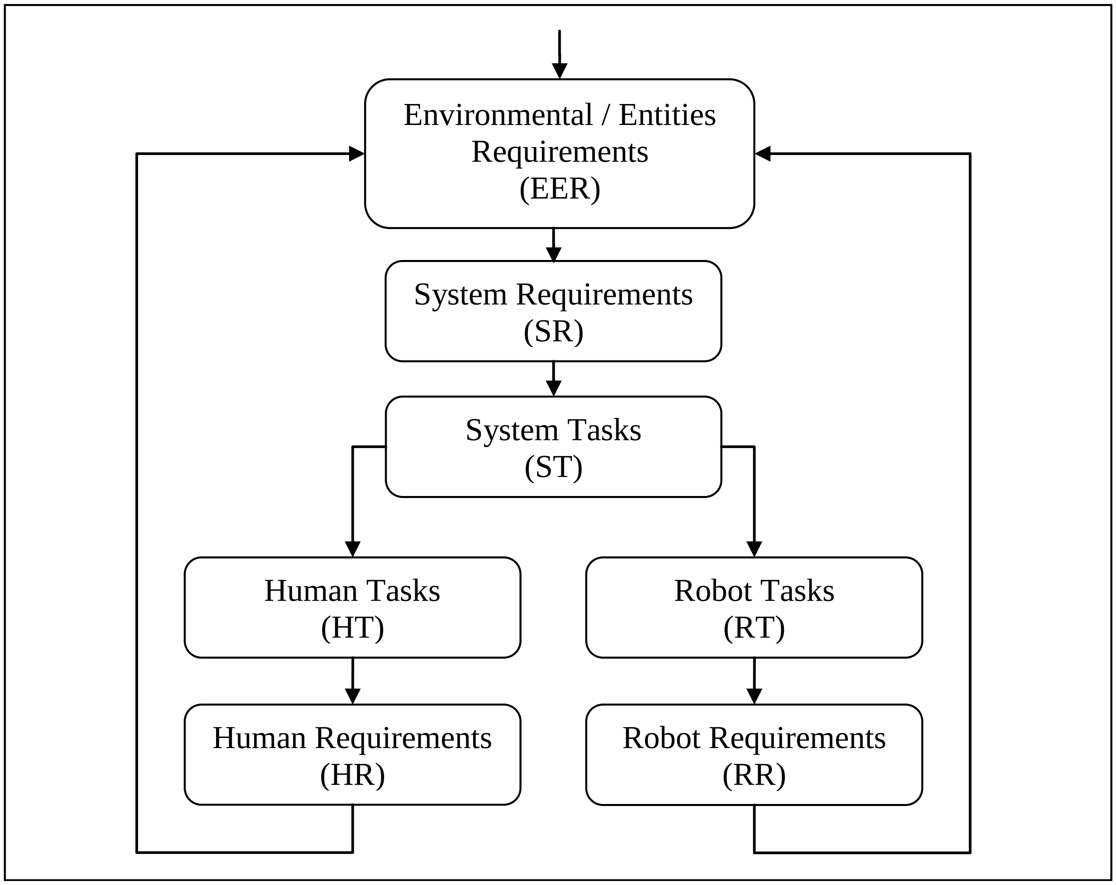

Figure 2: HRI Cyber-Human Requirement Model.

The model here presented aims to shed a light on how a robot engineering process should look-like. The first activity is to define a set of requirements for what the system is supposed to achieve. These requirements should be the content of layer SR. Research using user-centered design and goal-directed task analysis techniques are being employed to discover requirements for specific search and rescue activities (Adams 2005).

Based on this set of requirements, a set of system tasks are created on layer ST. These tasks may then subdivide into human-related and robot-related tasks. These tasks are going to be placed on layers RT and HT respectively. These tasks, on the other hand, are going to imply on a new set of requirements that are human and robot specific and that are going to be placed on layers HR and RR respectively. These requirements are going to be added and checked for consistency with the system requirements. If they are consistent, the new HR and RR requirements are added as derived requirements to SR. If there is inconsistency, the requirements of the system must be modified. After modifications are applied, the cycle is restarted. The model could be used for iterative optimization of requirements and tasks on an HRI system.

The idea behind this model is that, based on an initial set of requirements, new requirements for both human and robot parts of the system can be generated. These new requirements may imply in new modifications in the original system requirements. The system requirements may either be modified based on conflicting requirements or expanded to comprise more functionality. The new requirements are then re-applied to the model and generate new human and robot requirements. This optimization process may go on as new system requirements are added or as long as conflicts between requirements for the system and its human and robot parts exist.

This model may be applied to a specific set of requirements as, for example, situation awareness requirements. In this case, the process of requirements discovery may start either at the SR level or ST level and generate both human and robot SA requirements.

It is also important to relate this task-requirement model to a potential entity, be it a by-stander or an object, with which the system is going to interact using the robot side of the interface and also to the properties of the remote environment itself. That is, the system requirements must also include requirements related to interaction with entities and environment (EER). It is expected that the requirements mostly affected by this factor will be the ones on the robot-side of the system, though it might not always be true. As an example, if the human-robot system is required to collect fragile objects in the environment, the robot is required to have a sensitive hand, but the operator is also required to have high motor skills and experience in operating robot arms in order for the system to work as a whole.

It is believed by the author that the identification of the most basic primitives is of the utmost importance to the development of procedural techniques to evaluate user's performance and SA.

It is interesting to notice once again the symmetry between the robot side of the HRI system and the human side. The authors believe that the ideal robot would be a human interface on the robot side. In Virtual Reality, it is believed that the more natural an interface looks to a user, the higher is his levels of presence. The author believes that such concept can be extended to HRI systems. If the operator works on the remote environment as if operating his own body, it is likely that his presence will increase and, as a consequence, its performance as well. It is undeniable that some requirements are supernatural, such as infra-red or ultra-sonic vision. Nevertheless, this symmetry between operator and system and between system and remote environment is a point that has not been given much attention by the HRI community and that has been highlighted as extremely relevant by the VR community. In the proposed model, this symmetry can be captured by an equivalence relation between the human requirements (HR) and robot requirements (RR) or even between the human and robot tasks. Such equivalence may be considered as a strong indicator of the existence of symmetry between interfaces on both sides of the system and, hence, of a consistent and effective interaction system that lessens the cognitive load on the operator.

Above the higher level tasks are then the immediate goals of the mission that a human-robot team has to accomplish. Scholtz (2003) has applied Norman’s 7 stages of interaction to HRI. Her proposed model and its relation with users are presented in Figure 3 below. However, the division between *software* and *hardware* proposed by her was replaced by the concepts of *virtual* or *remote interface* and *physical* or *local interface* which appear to make more sense in HRI.

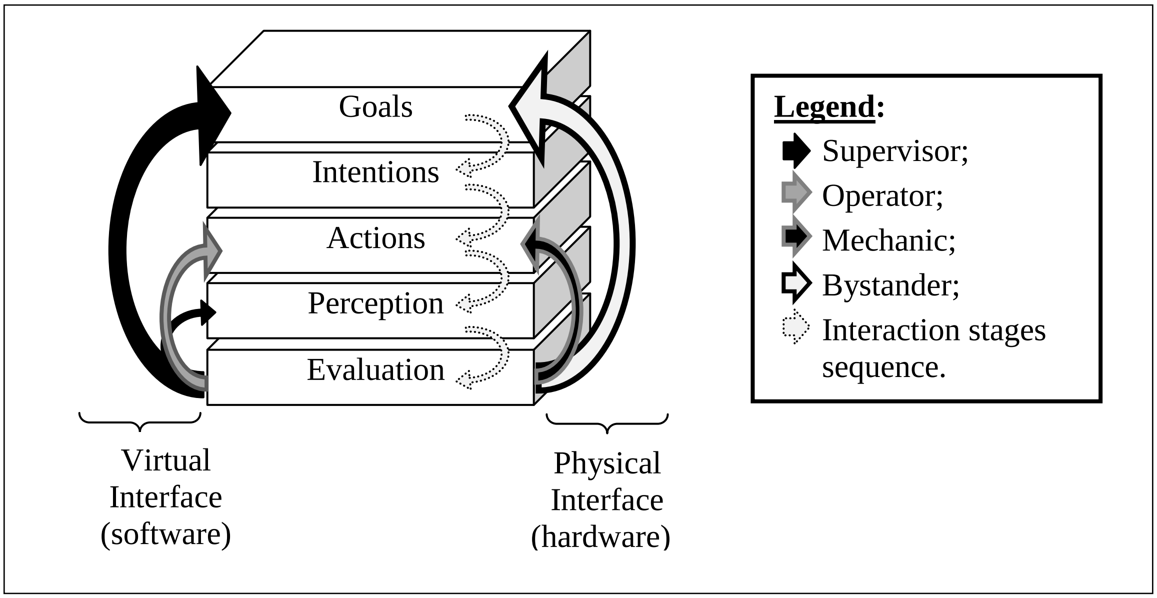

Figure 3: Norman's model for HRI.

It is interesting, nonetheless, to realize that in this model there is also a symmetric relation between supervisor and bystander for high level interpretation in either interface sides, as well as a similar relation between the operator and the mechanic. Table 8 below clarifies this relation.

Table 8: Symmetry relation among HRI users in Norman's model.

	Robot control	**Robot**
High level of abstraction	Supervisor	Bystander
Lower level of abstraction	Operator	Mechanic

It is evident from Figure 3 that users may be divided into the ones that deal with a higher level of abstraction and those that deal with a lower one. It indicates that a similar subdivision of the HRI CHuRM model could be applied to human requirements and robot requirements according to the users that relate to them, as presented in Figure 4. This division may comprise requirements not only for the four classes of personnel, but also for new environment and entities as is the case of by-stander requirements as presented in Figure 4. The final requirements, now partitioned in more specific groups are checked for consistency with the initial EER and SR requirements and a new cycle in the model is started.

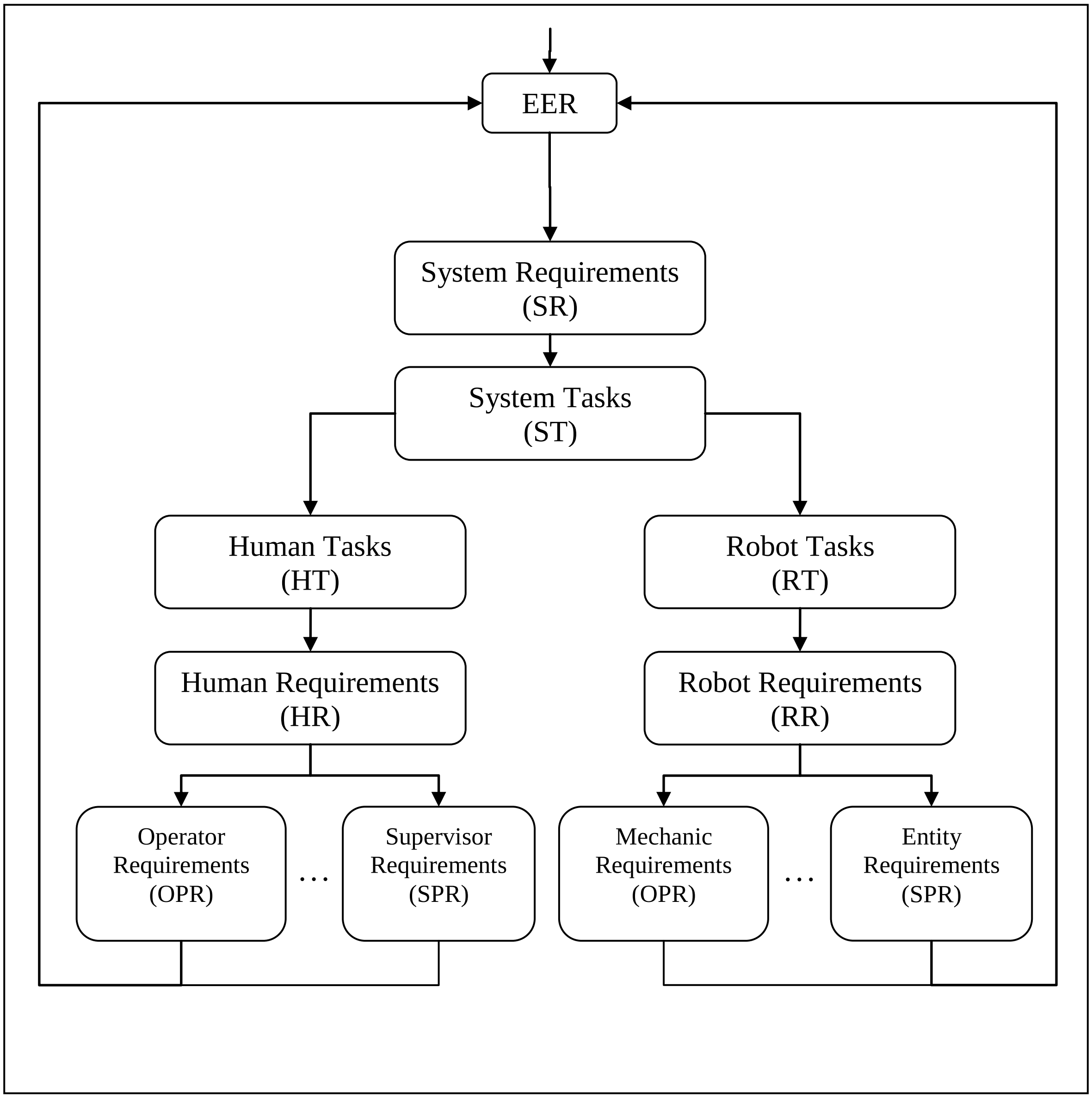

Figure 4: CHuRM extended to sub-level requirements.

4.4 Research areas:

Among the research areas that are closely related to HRI, two are Computer Supported Cooperative Work (CSCW) and Human-Computer Interaction (HCI). The former consists in the study, design and evaluation of techniques that allow collaborative work using tele-operation systems. The latter encompasses research on computer interfaces in general and how they affect their users in terms of objectively and subjectively measured parameters. HCI is a more mature area of research, when compared to CSCW, but is still under development for new areas such as 3D user interfaces and tele-operation itself.

4.5 Application Areas:

HRI techniques can be applied in a large number of areas, mostly those practical applications of robots in emergency critical situations. In addition, most of them are defined as field applications, where robots are exposed to unpredictable environmental effects and were robots are seen primarily as an extension of the operator (Murphy, 2004).

- **Urban Search and Rescue (USAR):** robots are used in tragic accidents to search for survivors and rescue them. Fireman and bomb squads are examples of specific groups that benefit from HRI techniques in their daily work. Casper *et al.* (2000) describe the different areas of actuation of USAR, such as hazardous materials (HAZMAT), bomb threats, collapsed buildings and trench rescue, and discuss issues with USAR in general and how robots can help in that matter.

  Three main tasks of a USAR robot are: victim detection, navigation and environmental monitoring. In a collapsed building situation robots can potentially be used for helping entombed victims by not only locating them but also bringing medical equipment. Most victims are easy to recover (50% are surface victims, 30% are lightly trapped, 15% are found in void spaces and only 5% are entombed).

  Casper & Murphy (2002) report that collision was the most common error during their USAR task, generally caused by either lack of sensors or communication failures. General hardware requirements for USAR robots include (Caper et al. (2000); Murphy, 2004): weather proof, intrinsically safe, water-resistant and sensor packages must not be hampered by contamination, should not threaten to cause an explosion in a gas-filled area, must be rugged, self-righteable, if turned over. Robots should not only be *reliable* (Osuka *et al.*, 2002), but also small, lightweight, have a wide range of sensors and reasonable computational power, as well as battery life. Murphy (2004) provides further details on the different types of robots and task in which they are used.
- **Military Operation in Urban Environments (MOUT):** as the name says, this area basically consists in any military activity using robots in urban environments. Examples of this are teleoperated vehicles for surveillance and for attack/defense of a territory (Hill & Bodt, 2007).
- **Wilderness Search and Resuce (WiSAR):** robots, generally UAVs, are sent to search and large wilderness area (e.g.: forests, deserts, sea, etc.) in search for survivors. Cooper & Goodrich (2008) have studied WiSAR tasks by experimenting with system parameters such as interfaces paradigms, navigational paths, searched-targets distribution and camera behavior.
- **Reconnaissance, surveillance and target acquisition (RSTA):** robots are primarily used as advanced exploratory tools (Burke *et al.* (2004)). Not only are robots used in spatial exploration outside Earth as publicly known, but also on Earth itself, at inhospitable regions where presence of human is hazardous or may imply in higher costs for long periods of time . Notice the importance of sensor

networks as an important monitoring technology. It should be used jointly with tele-operated robots to enhance the robot's perception of the environment.

- **Surgery:** tele-surgery is one of the first and most well-known applications of HRI to the public. Publicized by news agencies quite often, remote surgeries occurs when a very specialized surgeon is required to attend a clientele located in a large geographical area and is unable to travel from one location to the another in order to attend to all of them in time. The surgeon then performs some of the surgeries remotely by making use of high-bandwidth network connections and a very accurate and high-fidelity HRI interface. In this case, the precision and response of such an interface is crucial since a human life or health is at stake.
- **Robot Competition (AAAI):** Robots are mostly used in critical situations and in emergencies. These do not occur very frequently fortunately. However, this fact puts HRI research in very undesirable situation, since their research progress on any interface is directly related to how much it is being used and evaluated by skilled personnel. In order to separate the progress of HRI interfaces from incidents, robot competitions were created. Their main purpose is to divulge research in HRI and put the research theory into practice by simulating incident situations such as building collapsing and exploring difficult terrains. They aim to test the efficiency and efficacy in performing tasks that are common to tele-operated robots such as navigation, search and retrieval (Yanco *et al.*, 2004; Osuka *et al.*, 2002).
- **Spatial exploration:** Space exploration has always been an area of great interest for the robot community due to the harsh conditions that space imposes to men (Atherton *et al.*, 2006; Aubrey *et al.*, 2008).

4.5.1 Other 3DUI Techniques relevant for HRI

Research in HRI could benefit from the study that has been done in the area of 3D user interaction (3DUI). Both HRI and 3DUI areas deal with the problem of improving user interaction with a remote 3D environment, be it a real remote environment or a virtual one. The exchange of information would lead to progress in both areas since their research work would be in tandem with each other. Below, some of the 3DUI techniques that were deemed relevant to HRI are listed based on the work of Bowman *et al*. (2005).

The main difference between human-robot and 3D user interaction techniques is that, while the latter has unlimited access to information about the environment, the former is limited by what is given by the sensing devices, which might even be imprecise or incorrect information. Hence, although HRI techniques may very easily transfer to the area of 3DUI, the opposite is not always true or may not be a trivial task.

Below basic 3D user interaction techniques are defined. They are also listed according to their level of dependence on environmental information. The idea behind this listing is to identify how easily transferable the techniques are from 3DUI to HRI. The listing order is very general and it is possible that such order may change according to the complexity of the interaction task.

3DUI techniques may be divided into the following categories: selection and manipulation, travel, wayfinding, system control and symbolic input.

Symbolic Input consists in typing symbols of a language and transmitting those symbols either to the system or to other users. This is a common task in HRI and generally accomplished by using a keyboard or some type of touch screen. In 3DUI, a wider range of input devices are available, among them single-hand chord keyboard, voice recognition systems and different types of graphical representations of keyboards to be used in tablet PCs or handheld computers.

System control is also a common task in HRI and 3DUI. Again, some techniques used in 3DUI may well apply to HRI interfaces. The TULIP technique consists in selecting menus options using pinch-gloves. When the tip of the thumb touches the tip of any of the other four fingers, a certain menu option is activated. Since the number of options may be larger than four, touching a certain finger may also be used for mapping other menu options to the fingers. The advantage of this technique is that the user has the input device in its hands still keeping the latter free to perform other tasks. As an example, this input could be used on a hand operating a joystick. The user would not have to move his hand out of the navigation control in order to select menu options, thus, converging two tasks to a single hand.

Wayfinding is a subject in which both 3DUI and HRI areas are closely related. It consists in having some information of the environment and using that information for navigation purposes. Wayfinding typically boils down to maps and their task-directed cognitive analysis (Billinghurst & Weghorst, 1995). Two basic representations for maps are possible. The first one provides an egocentric view, where the location of the entity (robot or user avatar) is fixed on the center of the map being represented and the environment described in the map shifts or rotates as the entity moves. This type of map is useful when local attention awareness is important. The second type of map provides a geocentric view. In this view the entity orientation varies as it moves while the map orientation is fixed. If the map is larger than the available space on screen, the map may shift as the entity moves or as it reaches the borders of the area represented on screen. In the first case, the entity is always centered on the map representation, whereas on the second case the entity moves along the area representing the map. If the map is smaller than the area available to graphically represent it on screen or if it is scaled to fit it, the map has its position fixed.

Although some 3DUI travel techniques could be mapped to HRI interfaces, all of them need to be adjusted to the travel constraints imposed by the robot hardware. Interestingly, some more intuitive techniques, such as travel techniques are already being implemented. However, techniques that are related to body tracking, such as gaze or torso movement capture and input are not. Moreover, techniques as the WIM and voodoo dolls are impossible to be implemented for most types of applications.

Selection of objects that are presented by the video feed to the user is really dependent on the level of visual quality of the HRI system. If the system is capable of recognizing the shapes and types of objects, then, objects could indeed be identified and selected. The selection of an object could be used to edit them and identify as special entities in the environment or can be directly manipulated if the HRI hardware interface has the apparatus for it.

Manipulation in HRI is completely dependent on the hardware interface provided by the robot. Since hardware implementation costs higher than software, it is far more viable to use 3DUI to test possible manipulation techniques for a specific hardware interface than to build a hardware interface for testing each possible 3DUI manipulation technique. Although the second approach may lead to interesting and important interface results in the HRI area, the task oriented approach of HRI makes its occurrence unlikely.

It is also important to highlight the vast amount of research that has been done in VR and 3DUI in terms of user perception. Their results may also be relevant to the design of effective HRI techniques and interfaces. Some of these results are: the differentiation and applicability of rate and position control and absolute and relative values, whether degrees of analog input and degrees of freedom should be integrated and, last, where and when to use digital or analog data representation.

5 Validation and Verification

HRI interaction techniques, as well as interfaces, must be validated and verified before they are put into use. While there are a wide range of techniques for validating the results of an HRI system, verifying the results of a certain project is generally much harder.

Verification requires the acquisition of equipment that is if not identical, at least similar to the ones used in the experiment whose results are going to be verified , which implies in costs to which most groups are not willing to deal with. This is aggravated by the fact that research groups have robots that are typically designed to perform certain tasks. Hence, unless a set of research groups match in their equipment, verification in HCI is very unlikely to occur.

The rest of this sections deals with validation techniques that are commonly applied in HRI.

5.1 Experimental Strategies

Three types of strategies are commonly used when designing an experiment to evaluate an HRI system.

The first of them consists in evaluating the system by objectively measuring hardware and software performance when operated by a set of users, who may be experts or not depending of the system application.

The second experiment strategy is measuring the social performance of the system, that is, how much social interaction the system allows the user to perform and how facilitated and diverse is this type of interaction.

The third and last strategy used in HRI experiments consists in measuring the system psychological response on the operator. Situations and tasks considered as having different levels of difficulty by the community are presented to the operator. The cognitive load of the system on the user is then measured and a final psychological profile for the system is created.

5.2 Assessment techniques

There are many techniques to assess an HRI system. The techniques may be categorized as pre-experimental, experimental, post-experimental and atemporal assessment techniques.

As the names imply, the first ones happen before an experiment is performed, the second happen during the experiment and the third ones after the experiment was carried out. The fourth one comprises techniques that do not depend on the experiment.

Most techniques here presented evaluate either the system as a whole or the software-hardware part. There are other techniques, however, that evaluate the operator only, such as the widely used NASA-TLX (Hart, 2006; Parasuraman *et al.*, 2005; Nielsen *et al.*, 2007), which is applied during or after an experiment. Others are used to define how to measure certain parameters, such as awareness (SCAPE method) as mentioned by Yanco (2002).

5.2.1 Pre-Experimental Assessment

Pre-experimental assessment basically implies in following a set of guidelines during the development of the system. Although the level of application of the guidelines should somewhat be measured, their use may guarantee that certain properties or features of the system are well-defined.

Examples of guidelines include Scholtz's SA requirements & evaluation methodologies (Scholtz, 2003, 2002) and Drury *et al*. design guidelines for HRI (Drury & Hestand, 2004; Drury *et al.*, 2003). Below is a list of guidelines and suggestions based on the work of many research groups. They are divided according to their area of relevance.

Teamwork:

- Better teamplay from Parasuraman *et al.*, 2008:
  - Highlighting changes in the system;
  - Displaying future projections;
  - Visually integrating information;
- From Parasuraman *et al.*, 2005:
  - Communicate with humans in ways that follow the norms of human-human communication;
  - Etiquette rules should be considered;
  - A distribution of tasks/controls among operators should be done based on the attentional frequency required for each task/control;
  - A system to help the operator manage his tasks.
- Increase expressiveness of robot demonstrations experiences through tighter human-robot communication methods (Burke *et al.*, 2004).

Feedback:

- Provide feedback on automation states (Parasuraman *et al.*, 2005)):
- Inform state transitions or allow these to be consulted when needed (Sheridan, T., & Parasuraman, R. (2006));
- Extensively describe how each SA component is or can be associated with an incident or event in an activity/experiment. The association should be very well justified (Drury *et al.*, 2006).

Functionality:

- Support human-information gathering activities (Parasuraman *et al.*, 2005));

Automation:

- Offloading low-level control of the robots to the automation (Crandall & Cummings (2007));
- From Parasuraman *et al.*, 2005:
  - When using LOAs, provide several functional levels of abstraction, plan/constraints and temporal, sequential and conditional constraints on task performance with levels of depth.
  - Associate interface status with potential problems previously noticed and solutions associated with it. That is, help the user find problems and solutions for a problem that might be occurring when monitoring, or using an automated system;
  - Always have emergency/manual controls to override autonomous behavior and activity;
  - Ensure the human can double-check the results presented by the machine part of the system, for the latter is less aware of its own bugs/problems that can be detected by humans;
  - An HRI system should have a specialist monitoring failures based on historical/logged data;
  - Good automation etiquette should be non-interruptive (patient) instead of interruptive (impatient);
  - Automation should be designed including: common grounding, the ability to model other's intents and actions, inter-predictability, amenability to direction, an effort to make intentions obvious, observability, goal negotiation, planning and autonomy support, attention management, cost control.

Figure 5: List of HRI guidelines and suggestions.

Robot simulation has also been used as a pre-experimental assessment of HRI techniques. A virtual environment is used to realistically simulate interaction with the real world. Depending on the results obtained in the virtual environment, the implementation of the project may be followed by the design and testing of the robots and the system or redesigned and re-tested virtually (Lewis *et al.*, 2003).

5.2.2 Experimental Assessment

Experimental assessment may me done objectively, that is, without the intervention of an experimenter. Examples of this type of assessment are video monitoring and logging the software and hardware status. The positive aspect of this approach is that results are not biased by human intervention. On the other hand, some results may be inconclusive, such as video and audio monitoring, and may need data analysis by the experimenter a posteriori. In addition, the amount of data may be very large and take a long time to analyze, especially when human post-analysis is required (Yanco *et al.*, 2004).

Moreover, when information is collected objectively, it is still may depend on the behavior of the user or subject experimenting with the system. They may be required to give information during the experiment such as *thinking aloud* (Drury *et al.*, 2003) what they are doing or thinking. In this case, objective results may be biased by user personality and social behavior (Steinfield *et al.*, 2006). There may also be interruptions to allow the user to give their impressions about the task and the system. A very commonly technique for this is SAGAT and its derivations (Drury *et al.*, 2006).

Subjective assessment implies in the need of an observer or analyst to filter out the results that are important to the experiment. Examples of this type of assessment are information annotation using pen and paper and post-filtering collected data as previously explained for video monitoring. The positive aspect of such a technique is that only the necessary data is collected from the experiment. However, the collected data is always subject to bias caused by the observer perspective of what should or shouldn't be assessed and reported (Yanco *et al.*, 2004; Osuka *et al.*, 2002). A technique for acquiring subjective measures is SART (Parasuraman *et al.*, 2005).

There are some standard experimental assessment techniques that have been verified and are widely used. The first of them is Fitts' Law, which is related to the speed and accuracy of user movements of a cursor on a bi-dimensional interface. Other tasks that are commonly used to measure a system's performance in HRI are tracking and search tasks. On the first, the HRI system is required to keep track of a certain entity in the environment. On the second, the HRI system is required to recognize and count certain types of entities.

5.2.3 Post-Experimental Assessment

Post-experimental assessments consist in consulting the user about the system after the experiment is over. This is done using questionnaires, whose answers may be recorded using audio capture devices or pen and paper.

A general approach to measuring situation awareness is asking the operator to draw a map describing the places traversed by the robot (Billinghurst & Weghorst, 1995) and to locate victims in that map. Questionnaires also tend to ask about changes in the environment after or in-between tasks (Goodrich *et al.*, 2005).

5.2.4 Atemporal Assessment

HRI assessment may also be performed independently of experiments. The three common way of doing this are:

1. Inspection: the system is inspected by an expert;
2. Empirical: the system is assessed by applying a battery of tests to it, each of which may exam different aspects of the entire system or its subparts;
3. Formal: formal assessment of the system may be performed using mathematical and logical verification.

5.3 HRI Metrics

In order to evaluate the usefulness of any system, a set of metrics is required. In HRI, there are generic metrics that give an overview of what can be applied to any system, but that do not provide a lot of extra information on how to translate to the specifics of each system, and specific metrics, that are applied to a specific task.

There is a consensus, however, on more general metrics for HRI, such situation awareness and operator workload. How, to measure them, however, is the rest of this section is about. It describes other metrics that are commonly used in HRI.

5.3.1 Task Metrics

An HRI system may be evaluated according to a variety of task metrics. Here, they are categorized mostly according to the work of Steinfeld *et al.*, (2006), but also based on Crandall & Cummings (2007) and Goodrich *et al.* (2005). Some of them are recognized as general performance metrics that are system independent such as effectiveness and efficiency. Others are more related to HRI tasks only.

The metrics are categorized according to common tasks that are performed in HRI: navigation, perception, management, manipulation and social tasks.

Manipulation	- Degree of mental computation - Contact errors
Social	- Interaction characteristics - Persuasiveness - Trust - Engagement - Compliance

Figure 6: Common metrics for manipulation and social tasks.

- Navigation
  - Global navigation
  - Local navigation
  - Obstacle encounter
  - Effectiveness
    - Percentage of navigation task completed
    - Coverage of area
    - Deviation from planned route
    - Obstacles avoided or, not yet, but that could be overcome
  - Efficiency
    - Time to complete task
    - Operator time for the task
    - Average time for obstacle extraction
  - Non-planned looping /workload
    - Interventions per unit time
    - Ratio of operator time to robot time
- Perception
  - Passive perception
    - Detection measures
    - Recognition measures
    - Judgment of extent
    - Judgment of motion
  - Active perception
    - Active identification
      - Efficiency
      - Effort
    - Stationary search
      - Detection accuracy for targets within range
      - Efficiency as time to search or
      - non-overlapping coverage
      - Ratio of coverage to sensor coverage
      - Operator confidence in sensor coverage
    - Active search
      - Efficiency
      - Number of identification errors
      - Degree of operator fusion

Figure 7: Common metrics for navigation and perception tasks.

Management
- Fan out
  - Attention allocation efficiency
  - Interaction efficiency
  - Neglect efficiency
  - Switch time delay
- Intervention response time
  - Time to deliver request from the robot
  - Time for the operator to notice the request
  - Situation awareness and planning time
  - Execution time
- Level of autonomy discrepancies

Figure 8: Common metrics for management tasks.

The variety of metrics generally varies inversely with the task complexity and how general it is. Hence, the metrics for simpler or more common tasks such as navigation and perception are more well-defined than for social and manipulation tasks. The metrics hierarchies presented above are a good indicator of where progress is being done in terms of task understanding in the field of HRI.

5.3.2 Performance Metrics

An HRI system may also be evaluated by performance metrics. These metrics are divided according to which part of the system is being evaluated: the entire system or only the robot or the operator.

System
- Quantitative performance
  - Effectiveness
  - Efficiency
- Subjective ratings
  - Ease of use
  - Ease f Learning
- Appropriate utilization of mixed-initiative
  - Percentage of requests for assistance made by robot
  - Percentage of requests for assistance made by operator
  - Number of interruptions of operator rated as non-critical
  - Functional primitives decomposition
  - Interaction effort

Figure 9: Common metrics for system performance.

Operator
- Situation awareness
  - Human-robot
  - Human-human
  - Robot-human
  - Robot-robot
  - Human's overall mission awareness
  - Robot's overall mission awareness
- Workload
- Accuracy of mental models of device operation

Robot
- Self-awareness
- Human awareness
- Autonomy

Figure 10: Common metrics for operator and robot performance.

Most performance metrics are related to the entire system. However, metrics for specific parts of the system are being defined. Their definition of such metrics will lead to a better understanding of the effects that each part of the system has on the system performance as a whole.

5.3.3 Other Types of Metrics

HRI researchers have also defined metrics according to other features in the system, such as human robot ratio or type of robot.

Crandall & Cummings (2007) presents a set of requirements for classes of metrics that are designed specifically for human-robot interaction for 1 operator and multiple robots:

- Metrics should identify the limits for all agents in the HRI system, such as *interaction time* (IT), *neglection time* (NT)and *wait time* (WT);
- Metrics should have predictive power, such as predicting the fan-out capacity of the system and the average performance of its robots;
- Metrics should have key performance parameters that give an overall evaluation of the system, that enables the operator to relate a system state to a certain set of parameter values and hence that help identifying causes for a certain system behavior.

In robot competitions some of the common scoring parameters used are: amount of human involvement close to the robot in the arena, number of humans needed to operate the robot, number of victims found, accuracy in reporting of victims' locations.

6 Research Challenges in the Area

The challenges in the area of HRI are directly related to the broad applicability that robots have in our society.

In terms of autonomy and behavior, Dautenhahn (2007) defines two important challenges in HRI. The first of them, providing robots with long-term interactions, gives them the capability of adapting the way they interact with the environment according to the robots level of familiarity. Research results in this area directly relate the robots as having an adaptable behavior according to situations in our society that is acceptable as a human behavior (Bien & Lee, 2007). Mimicking human behavior has always been a challenge in both robotics and AI. Even for USAR tasks, Casper & Murphy (2002) refrains the need for AI support for performing a complete search coverage, collaborative teleoperation and topological mapping (Nielsen & Goodrich, 2006).

The second challenge is directly related to the first one. In order for robots to acquire this long term interaction capability, they are also required to understand abstract situations in the real environment. Imbuing this kind of capability to robots is not trivial either. Again, for USAR (Caper et al. (2000)), video and audio feeds, analog data transmission, wireless Ethernet are generally the only means to get data in and out of the robot. Specifically for USAR, signal of frequencies around 450Mhz are preferred for building penetration. But, that is not enough to perceive the environment as if the operator was there. Furthermore, the robot sensors should allow the operator to detect features in the environment that (s)he would not be able to detect even when being there in person. For that, integration with vision algorithms is extremely important. These will process image input according to what aims to be detected or monitored in the environment. Different from digital image processing, however, these algorithms should adapt to different conditions imposed by the environment, such illumination, dust and video quality. Mush is yet to be done in that direction.

Burke *et al.* (2004) provide an interesting perspective on issues for HRI research growth, including a list of research directions for the area of HRI, such as studies on levels of autonomy, cognitive studies on human limitations in H-R tasks, interaction modalities, scalable and adaptable UI. From their perspective, research on HRI should be focused on three categories: representation, cognition and control. They also report a need for well-understood benchmark domains. In addition, they questions related to robot functionality and human-robot relationships, such as how can we undo some of the robot actions in a real environment? How does the robot's physical form and personality affect such a relationship? What if the person attributes to the robot more intelligence than the latter has? Or as they say: "Is it possible that a user might prefer a more social robot but consequently get less done?" Broader questions are also under discussion in the field: Is the purpose of the HRI technology to serve human needs?

Form our view, the answer for this last question should be a resounding yes. The robot should be seen as a tool for either helping humans accomplish their tasks and understand more about their own selves. Taking it the other way implies giving rights to robots that only live beings have, thus leveling human creation to "natural" creation, which is, as we all know, a very controversial issue. From the authors' view, put into simple words, robots are tools, though very advanced ones.

Another point that must be left here for afterthought is related to HRI autonomy. Having both operator and the robot AI make decisions on the HRI system performance may work well for some systems. But, for all such systems, there must be delimitation between the levels of control that either are allowed to have sole access to at one time. In addition, one of the entities, either the human or the robot (preferably the human) should have complete override power over the other. Otherwise, an HRI system is likely to become a wild two-headed beast where two brains struggle to control one body and where nothing gets accomplished.

In terms of tele-operation, the main challenges nowadays are related to team cooperation and robot design. The former is increasing in importance as the robot's level of autonomy increase and more robots can be supported by a single-operator (Adams 2006). In addition, as the robots are being used each time more to perform less trivial tasks, coordination between operators, supervisors and robot groups is becoming a complicated problem whose solution requires the use of not only technological but also social and psychological skills. The latter is a challenge that is intrinsic to every HRI system. Despite being by far the oldest of the challenges in the field, due to the diverseness of applications, the definition of a standard robot design is still an open topic. Despite the non-standardization of the design of robotic systems, some common knowledge in terms of how to locate specific sensors and how many of each are necessary or which are best for a specific task already exists in the field.

7 Conclusions

Despite the idea of robots helping humans existing as science fiction in our society for quite a long time, the development of such technologies to be used in the real world involves a large set of challenges in a broad range of knowledge areas. This causes research in robot development, especially in HRI to occur in a slower pace than other areas.

In addition, the rarity of robot development standardization and the variety of problems that robots are required to tackle hinders the progress in the field, since the accumulation of knowledge in terms of robot design and development needs to be reinvented at every new project or at least for every new research group that joins the community. For these reasons, only manufacturing robots are predominantly produced in a large industrialized scale.

Such standardization is not common in hardware design and in terms of interaction it is still in its infancy.

Solutions for interaction problems in other areas, such as HCI and VR, could definitely be adapted and used by the HRI community. As an example, the lack of use of tracking devices limits the HRI interaction possibilities. The implementation of a mobile and easily deployable tracking system may trigger the use of trackers in the area of HRI. Once this is done, the robot community may benefit from the accumulated knowledge of the VR community on using this input device.

It has been refrained here the importance of the correct mapping between task, number of robots and number of operators. It is believed that the cognitive load that a system imposes to operators is directly affected by the subtle relation between these three factors. The definition of this optimal balance would then serve as a benchmark for robot autonomy research.

This work aimed at presenting and overview of the many human-robot interaction techniques, the technology that is being used, how systems are evaluated and measured and what are the main challenges in the area. It is believed that the standardization in the HRI area and the information exchange between this and closely-related areas are essential to the creation of a perfect symbiosis between humans and robots.

8 Glossary

Here is a list of terms that are commonly used in the HRI area and that may not be clear to the reader. They are defined in the HRI context, although some of them may also assume a broader meaning.

- **Accident:** a serious event that may have led to hazard to the HRI system, to the people involved with it or to the environment with which it interacted. It is generally caused by a consequence of the occurrence of a series of errors or incidents occurring during the operation of the HRI system (Parasuraman *et al.*, 2008; Dekker & Hollnagel, 2004; Dekker & Woods, 2002).
- **Affordance:** is the concept of how an interface allows the user to interact with it. Affordable interfaces allows the user to understand their affordances, that is, what they can afford the user to do with them, just by having the user look at (touch, listen to, smell) them.
- **Automation:** in the context of human-machine interaction, it can be defined as "a device or system that accomplishes (partially or fully) a function that as previously, or conceivably could be, carried out (partially or fully) by a human operator" (Parasuraman & Sheridan, 2000).
- **Cognitive overhead:** originally defined as a Web-related term (Conklin, 1987), it can be defined in HRI as the extra effort and concentration required from the user to perform a task using an HRI system interface when compared to the same task being performed using a default system interface.
- **Complacency:** Relying on the fact that a (sub)system will keep behaving the it has been during the last numerous checks, the operator reduces the state monitoring rate for such (sub)system to a lower rate generally below optimal, which may lead to the miss of important events in the state of the (sub)system. Complacency is generally associated as being a consequence of overreliance (Parasuraman *et al.*, 2008; Moray, 2003).
- **Compliance:** is taking the correct action without hesitation in response to an event or request from the system. Compliance is generally associated with the operator and not with the robot part of tan HRI system (Sheridan & Parasuraman, 2006).
- **Degrees-of-freedom:** In HRI and automation, it is the minimum number of variables that must be sampled in order to effectively assume a function or role in a system. In Virtual Reality and 3D User Interaction, it is the number of different spatial displacements and rotations in different axis that an object can assume or that an input device can provide that data for.
- **Error (Machine or Human):** a software/hardware fault or a human mistake;
- **Eutactic behavior:** this is an intermediate and optimal behavior between complacency and skepticism. It happens when the user monitors the HRI

system just a frequently as necessary to guarantee optimal performance (Moray, 2003).

- **Feasibility:** “The projected plan's ability to achieve the declared goal state within resource limitations” (Miller & Parasuraman (2007).
- **Incident:** an unexpected event that may have lead to a problem in the completion or performance of a task;
- **Out-of-the-loop:** refers to activities or decisions in a system in which operator or humans in general are not involved.
- **Overreliance:** the act of putting more trust into the hardware / software part of an HRI than one actually should.
- **Reliance:** is how reliable the HRI system in terms of status and alert reporting. If the operator cannot rely on the tools used for monitoring a system, (s)he cannot operate the system in an optimal manner at all (Sheridan & Parasuraman, 2006).
- **Risk:** In HRI, it is generally related to an activity or performance of a system. It is a subjective estimate of the negative impact caused by a problem or failure of that specific system. It can be defined as the cost of an error times the probability of occurrence of that error (Parasuraman & Sheridan, 2000).
- **Robustness:** quality attributed to systems that can still operate despite abnormal internal (e.g.: algorithmic errors) or external (e.g.: unexpected input values) behavior.
- **Skepticism:** is the opposite of complacency. In this case the user spends more time monitoring the system or monitors it more frequently than it is necessary to obtain optimal performance (Moray, 2003).
- **Task capacity:** defines the amount of work per time unit that a system or operator can handle.
- **Transparency:** is a quality generally attributed to the interface of a system. A transparent interface allows its user to interact directly through itself without hinder, hence the idea of transparency. The idea is that the user should interact “through the interface and not with the interface”.

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