Critical Considerations for Human-Robot Interface Development

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ABSTRACT:

The purpose of this paper is to draw upon the vast bank of Human Factors Research and indicate how the existing results may be applied to the field of Human-Robotic interfaces (HRIs). HRI development tends to be an after thought, as researchers approach the problem from an engineering perspective. Such a perspective implies that the HRI is designed and developed after the majority of the robotic system design has been completed. Additionally, many researchers claim that their HRI is "intuitive", "easy to use", etc. without including actual users in the design process or performing proper user testing. This paper attempts to indicate the importance of developing an HRI that meets the users' needs and requirements while simultaneously developing the robot system. There exists a vast pool of Human Factors research based upon complex systems. This research contains many results and theories that may be applied to the development of HRIs.

Introduction:

Many years of Human Factors research have shown that the development of effective, efficient, and usable interfaces requires the inclusion of the user's perspective throughout the entire design and development process. Many times interfaces are developed late in the design and development process with minimal user input. The result tends to be an interface that simply cannot be employed to complete the required tasks or the actual users are unwilling accept the technology. Johnson [Johnson 2000] points out numerous issues with Graphical User Interfaces. While Johnson's book concentrates on GUIs, many of the issues that are raised also apply to HRI development. Johnson list the following principles [Johnson 2000]:

- Focus on the users and their tasks, not the technology.
- Consider function first, presentation later.
- Conform to the users' view of the task.
- Do not complicate the users' task.
- Promote learning.
- Deliver information, not just data.
- Design for responsiveness.
- Try it out on users, then fix it!

The incorporation of the user into the design process has for many years been termed User Centered Design (UCD).

In addition to the work related to user-centered design, many years of Human Factors research has concentrated on Complex Man-Machine systems. Such domains include Air Traffic Control, Cockpit Design, Nuclear Power plants, and Chemical Processing plants. While these domains differ from robotics, there are many theories and results related to operator workload, vigilance, situation awareness, and human error that can also be applied to HRI development.

As an example of the parallels between the above-mentioned domains and human robotic systems, consider a domain such as Air Traffic Control. Multiple air traffic controllers monitor a particular air space. These controllers act in a supervisory role, while monitoring all the aircraft within their air space. One could consider the aircraft as individual robots and the controllers as the operators monitoring a large team of robots. Another example is the case of providing a team of operators on a large chemical processing machine with the appropriate information regarding all portions of the machines. Eastman Kodak's Estar Roll coating machines are very complex machines in which there exist many subsections that must be monitored in order to continually produce film base [Adams and Reynolds 2000]. The base moves through the machines very quickly making it difficult to monitor each individual section (including hundreds of valves, thermocouples, etc.) at a single instance.

The intention of this paper is to provide a brief understanding of the following areas of Human Factors research and indicate their incorporation into the development of efficient, effective and usable HRIs. The areas of discussion include:

- User Centered Design practices
- Human Decision-Making
- Workload
- Vigilance
- Situation awareness
- Human Error

A goal for HRI developers should be the creation of human robotic interfaces that are "humane". Raskin defines the humane interface:

> "An interface is humane if it is responsive to human needs and considerate of human frailties." [Raskin 2000]

Raskin indicates that in order to develop a humane interface the designers need "an understanding of the relevant information on how both humans and machines operate" [Raskin 2000].

User Centered Design:

> "User Centered Design (UCD) is a philosophy and a process. It is a philosophy that places the person (as opposed to the 'thing') at the center; it is a process that focuses on cognitive factors (such as perception, memory, learning, problem-solving, etc.) as they come into play during peoples' interactions with things." [Katz-Hass 1998].

The purpose of User Centered Design is to understand the user as well as the tasks and goals that must be achieved via the system. This understanding is then applied to the development and design of the interface the user relies upon to work with the specific system.

Katz-Hass defined the following questions with the intention that these questions would guide the user interface development process [Katz-Hass 1998].

- Who are the users of this 'thing'?
- What are the users' tasks and goals?
- What are the users' experience levels with this thing, and things like it?
- What functions do the users need from this thing?
- What information might the users need, and in what form do they need it?
- How do users think this 'thing' should work?
- How can the design of this 'thing' facilitate users' cognitive processes?

The general principle of User Centered Design is that the user plays an integral role during the system specification, design, development, and testing. There are many ways in which the users may participate. The initial step is to identify who are the appropriate users. If the user is a well-defined group, for example, college age males (18 – 22) who are electrical engineering majors at PhD granting institutions with at least 5 years experience using standard computing tools (Microsoft Office, Netscape, Explore, and email), then the task of including the appropriate users into the design process should be fairly benign. On the other hand, if the targeted user group is a general consumer, such as mothers of children under five years of age, then the ability to identify and include an appropriate pool of users in the design process is much more complicated due to the large size and diversity of the represented group.

In the case of HRIs, the developers should generally have a good understanding of the targeted user group. For example, in the case of Robin Murphy's rescue robots the users are two specific groups. The first group includes the incident commanders and the second group includes the robot control operator [Casper and Murphy 2002]. The application of HRIs for robots that assist the elderly represent a user group that is also fairly well defined [Czaja 1997, Ellis and Allaire 1999, Charness and Dijkstra 1999, Sit and Fisk 1999]. Once one moves to a few other domains, such as general military personnel, then the HRI design must consider the varying conditions and user capabilities. In fact, Newell and Gregor [Newell and Gregor 1997] draw a parallel between a soldier on a battlefield and a disabled individual. The battlefield environment can hinder the soldier's cognitive capabilities, as well as physical abilities (blinding dust storms or rough terrain). In addition to the environmental factors associated with soldiers using robots, the user group will not be as well defined as the case of Murphy's rescue robots. On the other hand, the user group will not be as ill defined as a general consumer group representing mothers with children under the age of five.

One key to the development of effective, efficient, usable, and deployable interfaces is the consideration of the user's needs and requirements. An initial consideration in the User Centered Design process is to examine such needs.

There are some simple considerations that the development team can consider prior to working with actual users. One such consideration is the environmental constraints and how the environment will constrain the interface design. Environmental constraints include: location, noise level, salience, temperature, accessibility, etc. In the case of a search and rescue task, it would be difficult to control the robot via a gesture interface if the robot is required to stay within sight of the human in order to be controlled. The intention with search and rescue robots is that they are able to access locations that are both dangerous and inaccessible to humans. On the other hand, Pirhonen et. al. recently presented the incorporation of speech and gesture into an interface in order to control a mobile music player [Pirhonen, Brewster, Holguin 2002].

As another example, the use of an audio alert system or audio user interface is not feasible for environments in which there is a large amount of background noise or in which the use of audio information would place the user in danger. The example of the Eastman Kodak Estar roll coating process represents a case in which audio information would not be salient. The noise level in the environment is such that the operators typically wear earplugs to block the majority of the machine noise. In the case of a military situation, a soldier out in the field may not be able to use an audio interface when there is a possibility that the audio would lead to enemy detection.

After the environmental and similar preliminary considerations are understood, standard UCD practice involves gathering initial representative user feedback via focus groups, ethnographic studies, and/or task analysis.

Focus groups are composed of a set of potential users (typically 5 – 10). The participants discuss the potential product and user interface concepts while providing feedback and identifying potential issues. A focus group session should "fell free-flowing and relatively unstructured" [Nielsen 1993] to the participants while the moderator follows a specified agenda that directs the discussion.

Ethnographic studies are intended to understand how real users complete actual tasks in their daily environments with existing tools and techniques. Ethnographic studies are able to identify how users work around their existing system issues as well as provide feedback regarding the desired interactions. Such studies are intended to "see activities as social actions embedded within a socially organized domain and accomplished in and through the day-to-day activities of participants" [Hughes et. al. 1994].

Task analysis permits the users to provide an analysis of a specific task. The data collection can be conducted via interviewing or surveying the users, asking users to keep a diary of task steps, user observation, or contextual inquiry [Jeffries 1997]. The result of the task analysis is a representation of all the tasks the user needs to complete with the system, the information the user requires to complete the tasks, the steps that the user must perform to complete each task, the interdependencies between tasks and task steps, as well as the expected results when a task is completed [Nielsen 1993]. The compiled data is employed to develop detailed task scenarios that can guide the system design.

The results from focus groups, ethnographic studies as well as task analysis are qualitative in nature. Nonetheless, such results can be very useful as a starting point in the design process.

The system design documentation should include the detailed user interface design. Software engineers and programmers do not typically represent the appropriate user group. Their perception of the user interface design rarely matches the actual users and/or Human Factors results.

The development of user interface prototypes should be completed early in the design cycle such that quantitative user testing may be conducted to validate the interface design. The quantitative evaluation should occur with each release of the system software. Unless the user group resides within the developing organization, it will be very difficult to conduct such an analysis with each software release. The intent is that the analysis should be conducted in an iterative manner. Since it is not feasible in many situations to conduct such iterative studies, the intention then becomes one of conducting user studies with an initial prototype and one or two future prototype generations. Such testing should be followed up with actual quantitative user testing employing two or three versions of the actual system implementation.

Only after appropriate quantitative Human Factors studies have shown that the design meets the requirements should the user interface be implemented. Testing can and should continue during the development cycle. Human factors testing needs to occur very early and frequently throughout the entire development process.

Nielsen states [Neilsen 1993]:

> "User testing with real users is the most fundamental usability method and is in some sense irreplaceable, since it provides direct information about how people use computers and what their exact problems are with the concrete interface being tested."

In the case of HRIs, it is proposed that the User Centered Design process and cycles can be applied. A significant change would require researchers to actually interact with their potential users. Many may argue gaining access to potential users is difficult, if not impossible. In fact, it may be difficult, but for many years Human Factors researchers have gained access to pilots, astronauts, soldiers, air traffic controllers, NASA's mission control, as well as the general consumer. Some HRI developers have conducted formal Human Factors studies [Adams 1995, Krotkov et. al. 1996] but these studies do not include actual users as the study participants. In the case of [Adams 1995], the participants were a mix a undergraduate students from various departments across the University of Pennsylvania as well as graduate students in the GRASP laboratory who had no relation to the multiple agent work. The results from this study meet the objective of determining if novice users would be able to control a mobile robot team, but these results cannot be extrapolated to combat soldiers, or rescue workers. Most recently Casper and Murphy reported on an ethnographic study conducted for the search and rescue domain that employed expert operators controlling the robots while trained rescue personnel guided the robot operator [Casper and Murphy 2002]. Additionally, Fong recently completed an ethnographic based study of collaborative control for human-robotic interaction [Fong 2001]. This study included participants who are considered novice users and represented students and laboratory personnel. While these examples represent individuals that are applying Human Factors techniques, many HRI developers are not.

Why is the User Interface Design Important?

The design of the human-robot interface can directly affect the operator's ability and desire to complete a task. The design also affects the operator's ability to understand the current situation, make decisions, as well as supervise and provide high level commands to the robotic system. While it is possible to spend a significant amount of time discussing specific interaction techniques, there is also a wealth of Human Factors research that can affect all HRI designs. Such research is related to human decision-making, situation awareness, vigilance, workload levels, and human error. Each of these areas should be considered when developing a human robotic interface. The remainder of this paper will concentrate on identifying existing research and a means of incorporating such research into the human robotic interface domain.

Human Decision Making:

The area of human decision-making appears to be an untapped resource for the field of HRIs. Humans make hundreds, if not thousands of decisions every day. These decisions are made rapidly in dynamic environments under varying conditions. Depending upon the human's current task, such decisions may have dire consequences if incorrectly determined, for instance, pilots during take-off, a chemical process operator during a chemical leak, and even any individual while driving their car down a busy street [Campbell et. al. 2000]. An understanding of the human decision process should be incorporated into the design of human-robotic interfaces in order to support the process humans' employ. The field of human decision-making research involves individuals making decisions as well as teams of individuals.

Gary Klien has conducted extensive research in human decision-making and in [Klien 1998] he attempts to "document human strengths and capabilities" in human decision-making. Since 1985 Klien has studied human decision-making with domain experts including firemen, pilots, nurses, and nuclear power plant operators, to name a few. The intent of his work is to identify how humans make effective and rapid decisions in a natural environment under difficult conditions.

Eduardo Salas and Clint Bowers are also fundamental contributors to research regarding human decision-making. In particular, they focus on how a system may or may not support the human decision making process. In [Oser et. al. 1999], they look at how training can affect decision-making when automation is used to support decision-making in complex systems.

The naturalistic decision making results from Klein's work may be applied to the development of decision-making and cooperation techniques for robotic teams. Additionally, his findings may affect the designed interactions between humans and robot teams. The work of Salas and Bowers can be applied to the design considerations that affect system training. The more complex and complicated the system, the more support it should provide to the human decision maker. In general, HRIs should benefit from the wealth of information available regarding human decision processes [Cannon-Bowers and Salas 1998, Mason and Moffat 2000, Sarter and Schroeder 2001].

Vigilance:

Parasuraman indicates that vigilance represents "sustained attention" [Parasuraman 1998]. Wickens and Hollands define the vigilance task as situations where "an operator is required to detect signals over a long period of time, and the signals are intermittent, unpredictable, and infrequent" [Wickens and Hollands 2000]. There are actually various characteristics that are incorporated into the definition of vigilance. Donald indicates that the following characteristics are incorporated into the common vigilance definition: "sustained attention, signals, detection, staying alert, being able to identity targets, and maintaining performance over time" [Donald 2001]. Maintaining vigilance can be affected by many factors. If the sensor information and/or operator tasks are infrequent and/or intermittent, the operator may become bored due to the lack of stimulation. This situation may lead to mental disengagement or even drowsiness. If the operator's vigilance level is low, it is possible that the operator's situational awareness will also be reduced. As is discussed in the Situation Awareness section, a reduced situational awareness can adversely affect the operator's decision-making process. There is also the possibility of too much information and/or too many tasks that lead the operator to work diligently in an effort to keep up with the situation.

While the operator is working on a particular problem, it is possible that the operator will not maintain vigilance over the entire system. In this case, the operator's decision-making process may be adversely affected.

Many factors beyond the actual sensory feedback and/or tasks may affect an operator's vigilance level. It has been found that lack of sleep [Swain and Scerbo 1995] as well as circadian rhythms [Huey and Wickens 1993] may adversely affect vigilance. Donald also points out that environmental factors, such as: "lighting, noise, ventilation, vibration, and temperature" [Donald 2001], often influence the operator's vigilance level.

Donald provides a general definition of vigilance that seems to fit well with the development of HRIs.

> "Vigilance refers to a capacity for sustained effective attention when monitoring a situation or display for critical signals, conditions or events to which the observer must respond." [Donald 2001]

Many situations in which the robotics community considers placing robots and the associated HRI, require operators to maintain their vigilance level. In the case of search and rescue [Casper and Murphy 2002], the robots are teleoperated with the expert robot operator being guided by the trained rescue personnel. This situation should keep both individuals involved in the task and therefore maintain their vigilance levels. On the other hand, many individuals speak of creating robotic systems in which the operator is simply overseeing the overall system. For example, a system with limited human interaction and primarily autonomous robots. While this is a technological goal that we would like to achieve, it directly implies that the HRI development must consider the operator's vigilance level.

Operator Workload:

The term workload may refer to mental or cognitive workload as well as physical and temporal workload. In general, high workload "can lead to reductions in vigilance as the person struggles to maintain accuracy and judgment under information and time pressure" [Donald 2001]. The case of underload (very low workload) can lead to the operator being under stimulated which may also lead to reduced vigilance, mental disengagement, and boredom.

Sanders and McCormick [Sanders and McCormick 1993] define mental workload as: "a measurable quantity of the information processing demands placed on an individual by a task." Each human has a different mental processing capacity. This mental capacity may be affected by lack of tasks to complete, stress, lack of sleep, environmental conditions, and even missing information. High mental workload may result in the operator making incorrect decisions that can lead to disastrous situations such as an airplane crash. Low mental workload may result in the operator not properly monitor the system and therefore losing situational awareness.

The Human Factors community has spent many years attempting to understand mental workload in order to develop tools that mitigate situations leading to high or low workload levels. It is well known that pilots' mental workload reaches a peak during landing and take off. The more stressful the particular situation the more likely that the operator's mental workload will be very high.

One aspect that must be considered in HRI design is the allocation of tasks between the operator and the robotic system. Mental workload measures play an important role in allocating tasks and should be employed not only for automatic task allocation but also in the initial HRI design and development to guarantee that the operator is not routinely over or under loaded.

Situational Awareness:

Another important aspect in Human Factors as well as HRI development is the maintenance of the operator's situational awareness [Endsley 1988, Endsley 1995, Endsley 2000]. Situational awareness refers to the operator's ability to properly understand the robotic team's activities in their current environment. In the case of robotic systems, the operator's situational awareness is already limited by the sensing capabilities provided by the robots.

Endsley provides a generally accepted definition of situational awareness [Endsley 1988]:

> "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future."

Situational awareness is difficult to measure in real settings and therefore most data collection occurs after the fact. Much work has been conducted in relation to air traffic control and major aircraft accidents [Adams et. al. 1995, Florian et. al. 1999, Jones and Endsley 2000, Prince and Salas 2000, Rodgers et. al. 2000]. Rodgers et. al. provide a review of situation awareness studies related to aircraft incidents [Rodgers et. al. 2000]. They also discuss the process employed by the Federal Aviation Administration and the National Transportation Safety Board when investigating such incidents. In fact, Rodgers et. al.

provide a description of the July 2, 1994 USAir DC-9 crash near Charlotte, North Carolina in which the pilots did not have a full situation awareness of the current weather conditions. Situation awareness has also been found as a contributing factor in the Three Mile Island incident [Reason 1990].

There exists a close relationship between situation awareness in a control room and an operator controlling a robot team. The operators in a control room monitor limited sensor information in which various sensory data points are distributed throughout a large system. The analogy applies to HRIs for remote distributed robot teams. The operator receives data from the various robots and attempts to determine the exact conditions and situation at the robots' site. For years, similar issues have been studied in the area of time-delayed teleoperation [Bejczy, Venema, and Kim 1990, Hirzinger 1993, Sayers 1999, Sheridan 1992, and Sheridan 1993]. Viewing limited sensory information (either the raw data or as processed via sensory fusion) is very restrictive when the operator is removed from the working site as well as when there is a large amount of data.

There also exists a close relationship between crew situation awareness in aircraft and military situations in which multiple individuals work together to operate a system. It has been suggested that multiple operators will be required to control large robotic teams. The understanding gleaned from the aircraft and military domains are good starting points for developing multiple operator HRIs.

In general, HRI design must strive to provide the appropriate information given the current situation, operator task distribution, and the operator capabilities.

Human Error:

Human error is the leading cause of various accidents. A very good example is the October 31, 2000 Singapore Airline accident in Taiwan. In this particular accident the pilots of a Boeing 747 aircraft taxied onto the wrong runway prior to take-off. The pilots did not realize that they had taxied onto the wrong runway nor that there was heavy construction equipment on the runway in their path. The result was that as the plane took off, it hit the equipment and crashed. There are many contributors to human error. In this particular case, the pilots were preparing for take off, a situation known to cause high mental workload. Additionally, the weather at that time was severe rain and monsoon type conditions. These conditions contributed to the pilot's inability to properly identify the correct take-off runway.

Sheridan defines human error as "an action that fails to meet some implicit or explicit standard of the actor or of an observer" [Sheridan 1992]. Sanders and McCormick define human error as "an inappropriate or undesirable human decision or behavior that reduces, or has the potential of reducing effectiveness, safety, or system performance" [Sanders and McCormick 1987]. Reason defines error as "… all those occasions in which a planned sequence of mental or physical activities fails to achieve its intended outcome, and when these failures cannot be attributed to the intervention of some chance agency" [Reason 1990]. In effect, Reason's definition encompasses Sheridan's as well as Sanders and McCormick's. Reason further distinguishes between error types, discusses error detection, as well as methods for reducing the risk of human errors [Reason 1990].

Much of the HRI research discusses the use of robots in cooperation with humans. In many cases the robots are working with humans in rescue situations or military domains. Human error has to be a primary concern in these situations. Work has been done with regard to direct robot human interaction and the dangers therein to the human from the robot [Nokata, Ikuta, and Ishii 2002], but very little work has studied the robotic system's failure being caused by the human. Both areas are important and require more focus. The available information from Human Factors can be employed as a starting point to understanding the affects of human error on the robotic system.

Conclusions:

The position that this paper attempts to present is two fold. First, the HRI community should approach HRI development from a Human Factors perspective rather than the engineering perspective. This includes further expanding the development team to include Human Factors professionals, as well as actual users while incorporating the HRI development into the robot development cycle. Secondly, the HRI community should attempt to build upon the existing and readily available results produced by the Human Factors community. Many of these results can be applied to HRI development while at the same time, new results will be discovered. It is important as the research community continues to move towards deployed robotic systems, that the developed HRIs prove to be effective, efficient, and usable.

This paper has covered some of the underlying concepts that should be considered in the development of human-robotic interfaces. These underlying concepts included incorporating the user centered design process into the robotic design cycle as well as the concepts related to human decision-making, workload, vigilance, situational awareness, and human error.

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In 2002, Adams [32] suggested critical considerations Fig. 1. An example of a completed worksheet for human-robot interface development. His concepts of User Centered Design and Situation Awareness guided us in the design of the proposed framework. Number of movements required to complete a leg Goldstain et al. [1] presented a methodology, which is In the experiment, a user step (movement) was defined as used for the design of the experiments in the next section. a single press on one of the controllerâ€™s buttons. In the The suggested methodology is based on the framework examined designs, the Critical considerations for human-robot interface development. JA Adams. Proceedings of 2002 AAAI Fall Symposium, 1-8, 2002. 124. 2002. Cooperative material handling by human and robotic agents: Module development and system synthesis. JA Adams, R Bajcsy, J Kosecka, V Kumar, R Mandelbaum, M Mintz, Proceedings 1995 IEEE/RSJ International Conference on Intelligent Robots and â€¦, 1995. 106. 1995.