Recommended Considerations for Human-Robot Interaction Communication Requirements

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Abstract. Emerging robot systems increasingly exhibit greater levels of autonomy, requiring improvements in interaction capabilities to enable robust human-robot communication. This paper summarizes the present level of supervisory control in robots, both fielded and experimental, and the type of communication interfaces needed for successful Human-Robot Interaction (HRI). The focus of this research is to facilitate direct interactions between humans and robot systems within dismounted military operations and similar applications (e.g., law enforcement, homeland security, etc.). Achieving this goal requires advancing audio, visual, and tactile communication capabilities beyond the state-of-the-art. Thus, the requirement for a communication standard supporting supervisory control of robot teammates is recommended.

Keywords: Supervisory control, autonomy, human-robot interaction.

1 Introduction

Combat teams increasingly consist of human ground troops and robot/unmanned assets. Robot assistance comes in the form of weaponized platforms, spy drones, and other Intelligence, Surveillance, and Reconnaissance (ISR) vehicles. The National Defense Authorization Act for Fiscal Year 2001 mandates the Armed Forces dramatically increase the use of unmanned and/or remotely operated systems to one-third of the ground combat vehicles employed in theatre [1]. The Unmanned Systems Roadmap presents strategies for meeting requirement by describing master plans for unmanned air, ground, undersea, and surface systems over the next 25 years [2].

A critical enabling capability for the successful implementation of tactically advantageous, but disruptive, robot systems within dismounted operations is effective and efficient HRI. Transitioning from continuous remote control (i.e., teleoperation) to supervisory control is essential to advancing HRI methods and to optimizing the employment of emerging military robot systems. Sheridan defines supervisory control as "…one or more human operators intermittently programming and continually receiving information from a computer that itself closes an autonomous control loop through artificial effectors and sensors to the controlled process or task environment."[3]. In other words, a human operator/controller commands a robot through a computer interface on a discrete rather than continuous basis. The operator programs

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actions the robot will take and the robot then executes. Throughout the tasking, the robot interacts with the operator and outputs information. This represents a closed-loop command and information exchange. For the purposes of this effort, supervisory control is operationally defined as operators/team members exercising discrete control of a robot, made possible by some level of autonomy the robot possesses.

Enabling the seamless integration of human and robot assets within mixed-initiative teams requires system developers to address four key concepts: (1) the type and level of automation inherent to the robot; (2) how humans communicate with each other; (3) interface design characteristics; and (4) human capabilities and limitations. The purpose for the present effort is to discuss each of these important topics with the aim of facilitating development of a supervisory control standard to drive development of next-generation robotic systems.

2 Level of Interaction

Three levels of HRI comprise supervisory control based on Rasmussen's "skills, rules, knowledge" and include: skill-based, rule-based, and knowledge-based human behavior [3] [4]. Skill-based robots perform a specific skill(s) with a given command. Rule-based robots are programmed to recognize certain stimuli and from those stimuli make pre-specified decisions. Knowledge-based robots essentially learn from their environment and make decisions based on that knowledge. When applying this paradigm to conventional robots and unmanned systems, skill and rule-based behaviors are found in currently fielded systems. Studies in knowledge-based behaviors continue to expand the area; however additional advancements are required prior to military deployment.

The three levels of HRI map directly to a robot's level of automation. Each branch of the military may tailor these definitions, but the core concepts apply to all. For example, leading research conducted by the U.S. Army suggests ten levels of automation known as Parasuraman's Levels of Autonomy [5] [6]. On this scale, one represents a system fully controlled by the human, and ten, represents a fully automated system. This concept parallels the two extremes in Rasmussen's Paradigm ranging from complete manual control to full autonomy. Using Rasmussen's paradigm, the following examples illustrate the levels of autonomy exhibited by various fielded and experimental systems.

2.1 Skill-Based Robots

Skill-based robots typically provide lower levels of autonomy, and require teleoperation to perform a particular skill given a command [3]. An example of this type of robot is a PackBot called the Valkyrie (see Figure 1). This remotely controlled Unmanned Ground Vehicle (UGV) used to extract a fallen Soldier from enemy fire is deployed to the Soldier in need. After the Soldier places him/herself on the Sked (i.e., bed), the robot encapsulates and carries them to safety [7].

2.2 Rule-Based Robots

Rule-based systems use predetermined stimuli to follow the commands of an “if-then” algorithm, [3]. The Global Hawk qualifies as one of these systems (see Figure 1). The main tasking for the Global Hawk is reconnaissance and surveillance achieved by employing an experimental multi-agent system. This system includes multiple UAV’s controlled via a single operator interface used to input mission relevant information. Global Hawk’s Human-Machine Interface (HMI) interacts directly with the operator and simultaneously maintains control of other system elements [8]. For example, when a lead UAV goes missing or becomes dysfunctional the HMI system reassigns an existing UAV on the same mission as the new lead. This occurs without input from the operator [9].

Similar to the Global Hawk, the Predator’s tasking focuses on navigation and surveillance. The Predator is equipped with hellfire missiles, which differentiates this system from the Global Hawk [11]. A need for armed combat systems capable of getting close to targets prompted the U.S. military to equip the Predator with weapons. Although this platform does not require continuous human input for flight and navigation, it relies on operator input for missile deployment (see Figure 1).

The Black Knight Unmanned Ground Combat Vehicle (UGCV) is an example of a research tool exercising ruled-based capabilities (see Figure 1). The Black Knight provides an operational test environment for Soldiers assisting in the development of UGVC tactics, techniques, and procedures. Capabilities such as a rule-based autonomous navigation system evolved from empirical experimentation. The Black Knight generates a path using autonomous capabilities that synchronize perception and path planning subsystems rather than relying on an operator to manually supply a route. The perception system senses obstacles and hazards, and coordinates with the path planning system to reroute and avoid detected obstacles [13]. Even though the Black Knight is not fielded, experimentation with this type of system demonstrates a foothold for future military vehicles.

2.3 Knowledge-Based Robots

Knowledge-based robots, as defined by Rasmussen, possess capabilities that assess a situation, and perform certain actions by considering multiple goals, decision points, and scheduling aspects [3]. Furthermore, robots with such capabilities currently exist in the research and development stages. An example scenario illustrating the goal level functionality of a knowledge-based robot is a commander tasking a robot to, “go to the back of a building and send me a picture of any person that leaves wearing a red shirt.” In this scenario, the system must identify the following subtasks: (1) move towards the back of the building, (2) monitor for someone exiting the building, (3) determine the person is wearing a red shirt, (4) take a picture of the person in a red shirt, and (5) report back to the operator with a notification and image. Accomplishing a task of this complexity requires knowledge-based system to understand the main objective, finding someone in a red shirt, and prioritize subtasks based on the main objective. If the system detects someone in a red shirt leaving the building before reaching the back of the building, it needs to execute the main objective of notifying its commander of the target of interest. These types of systems have yet to progress to field operations. Systems fielded today support skill and rule-based abilities; however a supervisory control protocol should support future capabilities including knowledge-based systems.

Fig. 1. Top left: iRobot Valkyrie [12], photograph retrieved with permission from http://robotfrontier.com/gallery.html. Top right: RQ-4 Global Hawk [13], photograph retrieved with permission from http://www.navy.mil/view_image.asp?id=125696. Bottom left: MQ-1 Predator [14], photograph retrieved with permission from http://www.navy.mil/view_image.asp?id=883. Bottom right: Black Knight UGCV [15], photo courtesy of the National Robotics Engineering Center. © Copyright 2007-2012, Carnegie Mellon University. All rights reserved.

3 Human-Human Interaction

3.1 Communication Process

Development of supervisory control standards requires evaluation of the human component of mixed-initiative teams in addition to robot skills and behaviors. Understanding the way humans communicate facilitates HRI. In human-human interaction the communication of a message involves three components; a sender, receiver, and a channel used to convey the message (Figure 2).

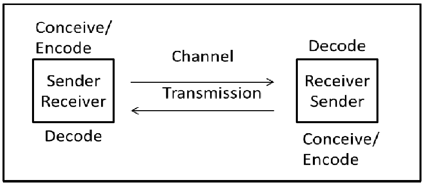

Fig. 2. Communication Process: Method used for human-human communication, the process begins with conception and ends with the receiver decoding the message, adapted from Weinschenk and Barker [16]

Communication begins with conception, when the sender creates a thought to convey to a receiver. The next step of the process, encoding, occurs when the sender considers which method to communicate the message. Transmission follows; in this step the sender selects the channel to convey the thought, ending the process of the sender [16]. The receiver then receives the message and decodes it. The process ends with feedback from the receiver verifying receipt of the message. At this time the receiver may opt to instigate a role reversal (i.e., receiver becomes sender) [16]. This process described by Weinschenk and Barker [16] for verbal communication is similar to the transactional model described by Barnlund [17], Figure 3.

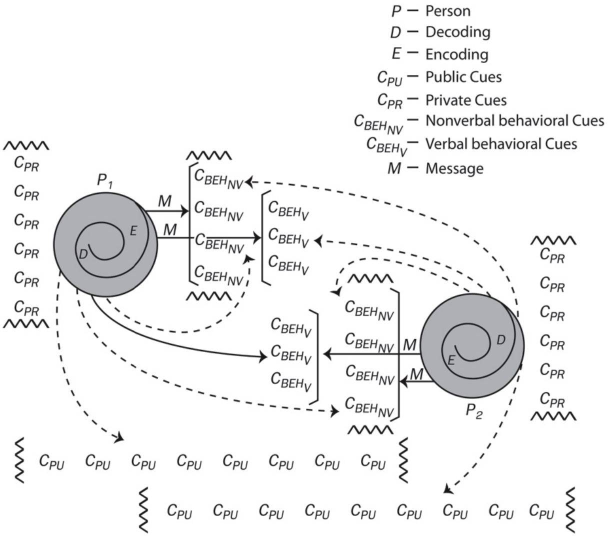

Fig. 3. Transactional Model of Communication, adapted from Barnlund [17]

The transactional model extends this process to include nonverbal behavioral cues (e.g., facial expressions, posture) and public cues (e.g., environment, culture), and thus, generalizes the model to include all explicit and implicit communication. Understanding the interaction models between humans, including communication modalities, is important in development of HRI.

Communication models demonstrate a variety of means to interact beyond speech incorporating combinations of explicit and implicit modalities. Explicit, or purposeful, communication methods consist of gesture and language. Implicit communication includes unintentional verbal and nonverbal behavioral cues and emotions. Published studies to date investigate explicit communications between robots and humans using auditory, visual, and tactile modalities. However, limited information exists in the literature related to direct application of implicit modalities for HRI [18]. Typically, the goal is to observe the robot's ability to understand the operator, acknowledge the command given, and then execute. However, research in the area Multi-Modal Communication (MMC) aims to improve communication by exchanging "information through a flexible selection of explicit and implicit modalities that enables interactions and influences behaviors, thoughts, and emotions [18]."

MMC emerges as a requirement as current and future robot systems move toward knowledge-based systems interacting with a commander, team members, and/or ambient society. As a result, the term "user" or "operator" is too limited to describe the types of people, and their roles, a robot may interact with during a mission. Following this reasoning, this effort uses the term interactor to include any person a robot interacts with. An interactor is either "active" or "passive" in their communication with a robot. An active interactor is a commander or team member able to give direction and tasking to a robot. A passive interactor is a person within society that a robot does not receive commands from, but may need to interact with through observation or other means.

By understanding robot capabilities and leveraging the study of human-human communication, HRI gains a firm foundation for developing effective interfaces. However, understanding the principles of interface and display design fills additional theoretical HRI gaps.

4 Interface Design

Since an interface serves as the bridge between a system and an interactor, the design must account for human and robot considerations. One example the HRI community can draw from traditional computer interface design is the list of Weinschenk and Barker's [16] twenty laws of interface design. Robotic system developers may derive clear interface requirements and design recommendations by adapting these laws.

The list presented in Table 1 focuses primarily on human factors considerations; however, questions related to where and how the robot will operate require additional consideration. Technical questions addressing the primary use of the robot and the type of hardware and software required arise. Understanding the physical environment (e.g., weather conditions) and the resulting effect on the interface design must be determined. Style guidelines regarding the look and feel of the interface play a role an interactor's perception and possibly performance. Ultimately, the goal is to develop an interface that fits the interactor, robot purpose, and circumstances.

Table 1. 20 Laws of Interface Design Applied to HRI adapted from Weinschenk and Barker [16]

Interface Law	Example
User Control- The interactor must think they control the system.	A speech application supporting interruption of robot operation facilitating perception of control.
Human Limitations- The interface must not overload limitations of human senses, (cognitive, visual, auditory, tactile, and/or motor).	Chunking words or grouping numbers reducing overload of short-term memory, which holds between five to n ine things.
Modal Integrity- The interface must fit the task, adapting modes of communication.	Commanding with speech and confirming with touch via pressing a button.
Accommodation- Match the interface for the interactor and the way they work.	Interface adjusts to support alternative communication modalities between normal and off-normal (covert) tasks.
Linguistic Clarity- The interface must communicate as efficiently as possible.	Interface transmits/receives appropriate terminology for communication mapped to the current context/task.
Aesthetic Integrity- The interface is designed to attract or repel interactor(s).	Using anthropomorphism to encourage interactor to engage system or deter interference from others.
Simplicity- Interface presents elements simply.	Interface facilitates natural interaction methods and common lexicon. Interface presents only necessary information without clutter.
Predictability- The interface behaves in a way such that the interactor can accurately predict what will happen next.	System executes commands consistently (e.g., system always stops when commanded).
Interpretation- The interface must anticipate what the interactor is about to do next.	When presenting a map the interface presents tools related to associated tasks (e.g., route manipulation).
Accuracy- The interface must consist of no error.	System interprets speech commands with accuracy greater than or equal to a human within multiple situations (e.g., noisy, quiet).
Technical Clarity- The interface must have the highest level of fidelity.	Visual interfaces present text and graphics clearly using appropriate fonts. Speech synthesizers articulate clearly and with appropriate dialect population.
Flexibility- The interface must have flexibility and customization capabilities for the user.	Interface employs MMC within dismounted operations. Operator control units supporting customized layouts for individuals or tasks.
Cultural Propriety- The interface must adapt to the customs and expectations of the user.	Interface prioritizes interactions based upon intra-team hierarchy. Interface interprets visual signals from different cultures correctly.
Suitable Tempo- The rate of the interface must match and become suitable to the interactor.	Interface presents information (e.g., speaks) at rate appropriate to the situational context and limitations of human perception.
Consistency- Consistency in an interface is a must.	A speech interface using “Go Forward” with “Go Back” as a corollary command rather than “Previous”.
User Support- The interface must support troubleshooting	Interface supports alternative input methods in the event of speech recognition failure and for system diagnosis. Alternatively, interface supports methods to query interactor for assistance (e.g., robot is disabled).
Precision- The interface must allow the interactor to perform a task exactly.	System responds as expected when given a command. For example, interactor requests information to the right of a target and a robot responds with results to the right of its orientation/location.
Forgiveness- The recovery of interactor actions is required.	Interface supports request for confirmation before performing unrecoverable actions.
Responsiveness- Effective responsiveness from the interface is required.	Interface provides progress indicator when performing complex actions.

Human limitations factor into what requirements a robot needs to properly communicate with its interactor. These limitations may affect the design and the type of communication modes used.

5 Human Capabilities and Limitations

A robot's level of automation depends upon the technology required to accomplish its mission or intended use. It also depends upon the technology available to achieve mission goals. However, understanding how to capitalize on the strengths, and minimize the weaknesses of a robot strikes at the core of mixed-initiative teams. In a broader sense, the term "mixed-initiative" indicates the optimization of role allocation for human and robot team members [19]. Thus, understanding HRI constraints resulting from human capabilities and limitations is necessary.

Capability constraints inherent to the human perceptual system, cognitive processing, and performance boundaries must drive the design, development, and creation of interfaces. Failure to recognize this need jeopardizes the success of interactions that will occur between a human and a robot. An average human maintains quantifiable thresholds useful for guiding the creation of HRI interfaces. We briefly describe cognitive, auditory, tactile, visual, and motor capability constraints of specific interest to this endeavor.

Cognitive aspects of note include memory, decision-making and attention. For example, chunking information serves as a common memorization technique for remembering five to nine items [16]. Research indicates that short and easy to remember commands or gestures improve communication accuracy in addition to efficiency [20]. Additionally, deficits in human decision-making capabilities suggest a need for a robot's interface to embody flexible recovery from human user mistakes. The ability to confirm tasking for high-risk commands would act as a failsafe to ensure correct comprehension of the task. In regards to attention, humans have a timesharing ability which allocates resources between two tasks. Ideal timesharing involves dividing attention between a auditory and visual input [21].

With respect to auditory capabilities, human hearing ranges from 20 to 22,000 Hz and from 0 to 130 dB (the threshold of hearing and pain) [16]. Human ears distinguish the direction of sound up to three degrees apart measured by the timing and strength of the sound each ear receives [22]. Weakness in hearing pertains to measuring distance of sound [23].

An interface that has a visual component presents challenges as well because of human capabilities. The wavelength visible to the human eye ranges from 400 to 700 nm [22]. Rods, receptors for nighttime vision, light sensitivity peaks at 500 nm, whereas cones (daytime vision) comprise of three peak sensitivities, 440, 540, and 565 nm for short, middle, and long wavelengths respectively [30]. Eyes adapt to darkness within thirty minutes of exposure [30]. For visual components, it is best to avoid overstimulation and information overload by eliminating display clutter. Font size and display size must be balanced to ensure clarity of messages and graphics displayed.

An emerging modality for robot-to-human communication is the sense of touch via tactile displays. Tactile displays transmit tactile-icons or "tactons" representing words or phrases [24] through vibro-tactile devices (tactors) typically around the abdomen [25]. Although it is still too early to determine if tactile displays are equivalent in utility to speech or visual interfaces for communication, designers must consider them in situations where other sensory modalities are overtaxed in respect to Wicken's multiple resource theory [26]. Research in advanced cueing applications with tactile displays shows no significant differences in reaction time compared to speech or 3-D Audio [27] alone, and demonstrates improved performance when combined with auditory cues [28]. Tactors on the torso also aid in navigation tasks and reduce workload [29]. Moreover, investigations into subjective workload and tactile displays in tactile cueing displays shows no significant difference in overall workload between tactile and visual cues with both showing lower workload than 3-D audio [27]. Even though the use of tactile displays may still be considered in their infancy, they may play a future role in multi-modal communication systems.

Motor acuity develops with practice. Research [31] [32] concluded humans practicing for short intervals spread out through several days learned efficiently rather than long intervals for fewer days [30]. In relation to tasks practiced, Shea and Morgan [33] concluded randomizing the order of learning the tasks resulted in better retention [30].

With regard to motor limitations, Fitts Law [16] [34] provides important quantifiable metrics for visual interfaces, it states:

$$MT = a + b * \log_2 \left(\frac{2D}{W}\right) \tag{1}$$

Where *MT* defines movement time, *D* the distance of the movement from start to center, *W* the width of the target, and *a*, *b* constants based on type of movement.

This law defines how large to make a target on a visual display, so the user can hit the target accurately. Even though a supervisory control standard would not focus on visual interfaces these constraints play an important role. Such capabilities and limitations impact the communication process between a human and a robot, and therefore are critical to setting boundaries for interface design.

6 Recommended Considerations

The topics presented above point to seven foundational recommendations that require expansion and enhancement.

1. Define the mission
2. Understand and account for the level of interaction supported by current and future robotic assets
3. Define cognitive resources required to support mission objectives and required level of interaction

4. Define the HRI communication protocols in terms of human communication processes
5. Develop an applicable MMC framework for HRI facilitating appropriate selection of communication protocols
6. Develop a set of science-based interface design standards
7. Define an HRI framework to account for human cognitive, auditory, tactile, visual and motor capabilities and limitations

7 Conclusion

Advances in robot sensor, autonomy, intelligence, and mobility are ushering in a new era of mixed-initiative teams. Communication between interactors and robots will be a critical factor in the success or failure of fielded robot platforms. The paper presents four key areas to consider when developing HRI standards focused on supervisory control: level of automation, human-human communication processes, interface design, and constraints based on human capabilities and limitations. Ultimately, the seven recommendations provided require expansion and investigation to fully realize the potential of mixed-initiative teams in operational environments.

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