Discussion of Challenges for User Interfaces in Human-Robot Teams

Frauke Driewer, Markus Sauer, and Klaus Schilling

University of Würzburg, Computer Science VII: Robotics and Telematics, Am Hubland, 97074 Würzburg, Germany {driewer, sauer, schi}@informatik.uni-wuerzburg.de

Abstract—This paper describes the challenges for user interfaces in human-robot teams and elaborates requirements considering the different roles that human can take over in such teams. The implementation of various test interfaces and observations from experiments support the claimed requirements.

The discussed human-robot teams consist of a remote supervisor and several team members (humans and robots) in the workspace. Humans and robots incorporate their different capabilities into the team for the accomplishment of a common goal. The supervisor guides the team and monitors the overall situation. The humans in the workspace work side-by-side with the robots and interact with them as peers.

Index Terms— Human-robot interaction (HRI), Human-robot teams, teleoperation, user interfaces.

I. INTRODUCTION

T HE integration of mobile robots and humans in joint teams working on a common goal is a desirable, yet challenging task. Fully autonomous robots or even multi-robot systems are not yet feasible. Humans still outperform the robot in e.g. cognition or reasoning. Moreover, for many potential application areas the complete substitution of people by autonomous entities is not advantageous. Often, successful human team structures are already established and the robots shall be integrated as team partners. Example applications are search and rescue [1] or teams of astronauts working on planetary surfaces [2].

In human-robot teams people can have different interaction roles. Scholtz *et al.* describe in [3] five different models: supervisor, operator, mechanic, peer and bystander. In real world applications and human environments it is likely that a robot has to interact with people in any of these roles. This implies high challenges for robot and autonomy design, control schemes and task allocation as well as human-robot communication and interaction.

This paper deals especially with the challenges that appear for the design of user interfaces for the human team members



Figure 1. Human-Robot Team Structure

(considering the roles of supervisor, peer and operator) in team structures as outlined in Figure 1. One typical task for this teams is the exploration of a partly known environment and the search for objects, as it occurs in search and rescue where robots are used to identify dangerous areas and for search e.g. of victims or fire sources.

This paper contributes a discussion of challenges for interfaces designed for the human team members based on related literature and own experiments. Example approaches for graphical user interfaces (GUIs) and the used robot and system architecture features are presented.

II. INTERFACE CHALLENGES

In a scenario as proposed in Figure 1, GUIs provide the main source for the humans to receive information from the environment and to interact with other team members. Therefore, the interface can be a bottleneck in the system, i.e. it can either hinder or support the task performance.

Related literature and own experiments revealed several challenges for interface design in human-robot teams. The next sections (A-E) summarize different interface challenges, which should not be seen a separated issues, but interdependent.

A. Display of Information

It is essential to analyze, which information is relevant for which team member at what time. It has to be decided how data from different sources is pre-processed, fused, and presented. Actual sensor data and information that is known before have to be combined with observations made by the human team members into a common environment and situation model. If the supervisor has to share the attention between several entities it is required that he/she can quickly recover the necessary knowledge (position, status, task, local surrounding, capabilities ...) when switching to another entity.

Display of information is maybe the most elaborated challenge for human-robot interfaces and possibly one of the most important issues since without information from the remote scene also other challenges cannot be met.

Many evaluations of user interfaces for teleoperation of mobile robots have already been performed and some have even resulted in guidelines. For example in [4] observations from the RoboCup Rescue and resulting guidelines for information display are presented. The results show the need for (a) a frame of reference for position relative to environment (b) indicators about robot status (c) information from several sensors displayed in an integrated fashion (d) the ability for self-inspection and (e) automatic presentation of contextually-appropriate information. Goodrich and Olsen [5] developed seven principles for efficient HRI, which are based on various experimental evaluations. Some of their principles relate also to information display (e.g. use of natural cues or support of attention management).

The problem of enabling an operator to get the needed information in dynamic situations has also been described extensively under the concept of situation awareness (SA). Endsley (e.g. in [6]) explains SA as the perception of information in a current situation, the comprehension of the information pieces and the projection into future events. Recently, SA has also been found to be very important for remote operation of mobile robots, e.g. real search and rescue incidents and field exercises reveal among other lessons that building and maintaining situation awareness is the bottleneck in robot operation [1].

B. Communication

Communication between the human team members is most naturally and fast done by spoken language (audio transmission). Communication between humans and robots seems to be more difficult, as current artificial systems do not provide the ability to discuss a situation or a decision. Nevertheless, the robots (and humans) might send messages e.g. that they found an interesting object or that they reached their goal position. If the supervisor is contacted by several entities at the same time the presentation of these messages has to be very efficient. Incoming messages have to be prioritized and sorted.

Fong *et al.* [7] describe the concept of collaborative control, which is based on an event-driven human-robot dialogue. The robot asks questions to the human when it needs assistance for e.g. cognition or perception, i.e. the human acts as a resource for the robot. Since the robot does not need continuous attention from the operator, collaborative control is also useful for supervision of human-robot teams.

Other forms of communication between human and robot are e.g. gestures for direct communication or an approach introduced by Skubic *et al.* [8], which uses sketches to control a team of robots.

C. Control and Navigation

Typical input devices for control and navigation are joysticks, gamepads or keyboard. More advanced methods could be based on speech or gesture recognition.

Navigation of the robots can vary from full teleoperation to autonomous movements. When multiple entities are controlled by the same supervisor some autonomy should be provided for the navigation (e.g. waypoint following). Nevertheless, in most applications it is necessary that the robots can also be teleoperated, e.g. for moving close to some object or even move the object itself.

Mixed initiative [9] and adjustable autonomy [10] describe concepts that allow varying levels for robot control.

For robots with a rather high level of autonomy, supervisory control [11] approaches are often used. It allows the user to enter high-level commands for monitoring and diagnosis of the robot. Providing this type of control makes the system capable to work even under low-bandwidth conditions or time delay in the communication link.

Autonomy of the robots or the system requires a careful consideration of these features in the user interface design and implies the next interface challenge.

D. Awareness of Autonomous Behaviors

If the robots are not completely manually controlled, i.e. they can take over control about themselves by certain autonomous behaviors, the human operator has to be properly informed about the action of the robot. Otherwise, frustration and mistrust might result. The user has to fully understand why a robot behaves like it does. Particularly, changes in the level of autonomy are critical. At best, the user interface supports combining the skills and capabilities of humans and robots.

The authors of [12] show a theoretical model for human interaction with automation that can be applied for automation design. They also explain problems that can occur with highly automated systems, e.g. reduced operator awareness of the dynamic environment or skill degradation.

Various studies analyze how humans interact with autonomy, e.g. Goodrich *et al.* show in [13] observation from four experiments regarding autonomy in robot teams. In [14] it is mentioned that users had problems to understand if the robot is in an autonomous mode and that users seldom change the autonomy level. As a result of their studies they propose to gives suggestions for mode selection in the interface.

E. Support for Coordination and Task Allocation

In the presented team model the supervisor is responsible for task allocation and coordination of the team during task performance. Therefore, the interfaces need methods to support the supervisor in understanding the status of the overall mission, the task performance of the group, and the individuals as well as provide support for communicating the allocated tasks to the related team member.

In [15] task lists are proposed as GUI elements for interaction with multiple robots in a remote environment. Fong *et al.* describe in [16] their human-robot interaction operating system, which supports task coordination and the management of task execution.

F. Human-Robot Teams

The last sections have elaborated interface challenges. Many of the above mentioned references concern single robot or even multi-robot teleoperation. Fewer studies have been taken out with similar teams as proposed in Figure 1.

Burke *et al.* [17] participated with robots in training of urban search and rescue personal. In [2] a system is described, which integrates astronauts and robots as peers for planetary applications. In [18] a study on teamwork with a science team, an engineering team and a mobile robot is shown. The authors found that grounding is needed for efficient team structures.

Nevertheless, the mentioned guidelines and evaluations provide a starting point for designing GUIs for such humanrobot teams. Other areas can also be used as resources for efficient GUI design. For example, [19] explains how approaches from the area of human-computer interaction can help to design interfaces for HRI. In [20] we describe the application of relevant GUI guidelines for teleoperation interfaces in a search and rescue application.

Another approach for understanding human-robot team work is to analyze existing human team structures. Before our research in the area of human-robot teams started a user requirement analysis was performed to evaluate potential enduser needs and wishes for rescue robots [21]. Jones and Hinds [22] studied SWAT (special weapons and tactics) teams in training in order to transfer the observations made into the design of multi-robot systems. Adams [23] described requirements for HRI by analyzing human teams from a bomb squad and fire department.

III. TEAM SETUP

A. System

The proposed team setup (Figure 1 and Figure 2) consists of a remote coordinator, who is responsible for coordinating and guiding the team. Therefore, he/she needs an overview about the environment and the team's overall situation. Moreover, he/she needs to know, who requires special attention or support.

The team inside the workspace comprises human and robot members. The robots have (semi-)autonomous features and sensors for localization and environment perception. The human team members have typically a notebook with a user interface available and possibly a human localization and assistance system [24], which provides the user with position and a local map from laser data. The team shares data over a central server.



Figure 2. System architecture. Pictures are taken from a prototype demonstration in a fire training house.

B. Software Architecture

The software architecture is based on a client-server architecture [25]. The server is the main component for data sharing. It takes care for configuration management (current status and configuration of the team members and the environment), persistence (log files and configuration of the system) as well as authentication and authorization of clients.

Humans (with their user interface) and robots (with their on-board software) represent the clients in the system. The architecture uses Java RMI, such that the client software can request information from the server in a standardized way. Clients and server are implemented with Java.

The server provides also other capabilities as maintaining an environment map [26] and a cooperative planning tool [27]. Video and direct teleoperation data are not communicated via the server, but over direct connections.

C. Robots

For several different robots software clients that can connect to the server exist. For the HRI tests mainly Pioneer I and II are used. However, for outdoor and indoor car-like mobile robots connections also exist.

The differential drive Pioneer robots are used as they implicate fewer difficulties for navigation and path planning. The research taken out with the human-robot teams is currently performed in unstructured indoor environments to keep the general navigation task rather simple, but still realistic, and that experiments are concentrated on HRI issues. The robots are equipped with localization, ultrasonic sensors or laser scanner for obstacle avoidance and normally a camera for environment perception. The client software updates the robots' position regularly in the server and creates messages if the robot encounters problems, e.g. the battery is down, the robot got stuck, or detects an obstacle in front.

The robots have some autonomous behaviors, e.g. they can move along given waypoints. They can also detect markers in the environment and moves then towards the marker position. When used together with the waypoint mode, the robot will stop at each waypoint, move around with its pan and tilt camera and searches the images for markers. The marker detection system is based on the ARToolkit [28], which was initially developed for tracking in augmented reality. If a marker has been detected the robot sends a message with the position and the marker identification. The markers are used to represent different objects in the environment, which shall be detected and identified by the robot.

IV. DISCUSSION ON USER INTERFACES

A. Requirements for the Different Roles

Considering the roles from [3], the *supervisor* is responsible for monitoring and controlling the overall situation. The *teammate* (*peer* interaction) can command the robots, but the ability to change the overall goal/plan stays with the supervisor. The *operators* change the robot's behavior, for example assigns waypoints or teleoperate it with a joystick.

In the presented team setup people can take over the supervisor or the teammate role. Both can also switch to the operator role. Therefore, two types of user interfaces are needed. One is for the supervisor, who sits outside the workspace and has therefore less restrictive hardware requirements (e.g. a standard computer with one or two monitors). The other user interface type is for the teammates, who work co-located with the robot in the workspace and move normally around. Thus, they have to rely on portable devices (e.g. laptop or even smaller device). Both user interface types have to provide support for the operator role.

The major requirements for the proposed scenario are compiled in Table 1, which was elaborated on basis of own user testing with three implemented interfaces (more details can be found in [29], [30], [31] and [32]) and the earlier mentioned literature.

B. Implemented Interfaces

At first, two interfaces (Figure 2 top and Figure 3) were developed for a prototype of a human-robot telepresence system for fire fighting applications [33]. For a detailed description of this interfaces refer to [29] or [30].

Both interfaces make use of the same graphical elements adapted to the needs of the human's role in the team. The main element of both was a global map of the environment with the position of the team members and path data, which was organized in layers such that currently irrelevant information could be faded out. The supervisor was able to update the map with new information. Buttons for map updates and setting paths allowed the supervisor to support the team members in the workspace. The teammate additionally had a local map based on laser range data. Together with path data and a direction arrow, this was used for navigation in dark areas.

 Table 1. Requirements for user interface for supervisor and teammate

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		Supervisor user interface	Teammate user interface
SITUATION	Overview about the complete environment	A global map/model of the environment is very important, such that the supervisor can execute the main task of monitoring and guiding the team. Information in the map includes structural data, position of team, semantic	Information about the global environment should be present only if it is relevant to the actual task (e.g. structural, path data and gas valve if a certain gas valve should be found) or influences the
		information (emergency exits, gas valves, or any other related to the mission),	teammate's situation (fading in dangerous areas close by, which might endanger the human).
	Knowledge about local environment	The representation of the local environment is required if the supervisor interacts with a certain entity (e.g. teleoperating a robot, analyzing a certain behavior or communicating with a human team member).	The teammate needs knowledge about the own local environment and similar as the supervisor if interaction with a certain other team member is required.
MISSION / TASKS	Goal and task allocation	The supervisor has to keep in mind the overall goal and is in charge to adapt the overall goal/plan. Therefore, a representation of the allocated specific tasks and support for associating and communicating new tasks to the related entities is needed.	The teammate should know the overall goal, but needs to know basically the own current task and potentially future tasks. If necessary, the teammate has to get access to the task allocation of the robots.
	Work load and progress of each entity	As the supervisor has to manage the resources of the team, she/he has to keep track about the work load and the progress of task execution of each entity. This should be visualized appropriate in the interface.	The teammate should be able to request work load and progress of other team members in case he/she needs help.
ENTITIES	Comprehension of entity behavior	Understanding the current level of autonomy (e.g. when the robot starts an autonomous behavior to avoid an obstacle or if the supervisor changes the attention to a new entity) is difficult for an operator. The interface has to provide adequate support for understanding the entities' actions and behaviors.	The teammate has to be informed about the behavior of robots near to the own position.
	Comprehension of entity relations	The supervisor has to understand from the interface if two or more entities interact directly, e.g. if a teammate teleoperates a robot.	The teammate needs information about entity relation only if he/she wants to directly cooperate with a robot or another human.
	Status and capabilities of entity	Status and capabilities show the supervisor if a robot is able to perform a certain task. Both should therefore be represented in the interface. Moreover, the status visualization informs the supervisor if an entity needs help.	Both should be available on request, e.g. if support from another team member is needed the teammate can check, which entity has the needed capability.



Figure 3. User Interface for Teammate

Human team members could communicate via audio. Additionally, a message system was implemented. Both, teammate (by pressing a button in the GUI) and robots could send messages about found victims or dangerous places. A reduced interface for the teammate exists if the human localization and assistance system is not required and the human only works with a laptop.

The above mentioned interfaces were tested and as a result of the evaluation the supervisor interface was enhanced such that the environment is presented as a 3D-model (Figure 4). A camera image can be shown in the middle. The map layer display lists all included objects (upper right). Moreover, the message system was improved such that incoming messages are sorted according to their priority (lower left).

C. Implementation of Requirements

1) Situation

The main source of building situation awareness in the presented interfaces is the 2D-map or the 3D-model of the environment. These include also the positions of the team and other non-structural data. According to the tests using a 3Dmodel supports the user, as humans are conversant with a 3D representation. If sensor data (e.g. ultrasound) is integrated, the spatial relation between different sensors is more intuitive. Moreover, it is easier to register the camera images into the model, as it can be seen in Figure 4. In the camera images a marker can be seen, which represents a dangerous object in the test. In the 3D view, the object is represented by a dangerous object icon. This makes it easy to understand the correlation between both representations from the environment. Except from the icons, 3D-labels and snapshots [34] can be added. With these features the model can be augmented by user-driven semantic information.

For the teammate interface a 2D-map appears sufficient. In the interface in Figure 3 it can nevertheless be seen that the map was overloaded by information. The buttons for fading out layers were never used in our tests, since the teammate was too busy to decide which information is currently relevant. Moreover, it was difficult for him/her to keep track on map updates. For time-critical applications, as e.g. search and rescue, it is required to improve the selection of presented global information to the teammate and provide appropriate highlighting of new or important information.



Figure 4. User Interface for Supervisor

The local environment representation with the laser map worked very well. Users appreciated it very much if they had to move through dark areas in our test.

2) Mission/Task

As all implementations are mainly used for exploration and search with currently only small teams, mission and task allocation as well as work load and progress visualization were not considered in detail in the design. Maintaining the mission and task allocation is left to the supervisor. Nevertheless, tasks (in the form of paths) can be associated and communicated.

If more complex missions and larger teams are required, new features have to be integrated. In the performed experiments the supervisor mainly concentrated on a single team member even if the team was small (one/two robots and one human teammate).

Implemented features for supporting the mission are the 3D-labels and snapshots. Adding these to the model helps the supervisor to maintain a history of the mission.

3) Entities

The team members sent messages if they found an object or encounter a problem (e.g. obstacle in front). The message system was one of weakest points in the first version of supervisor interface. When many messages were received at the same time, the supervisor completely lost the overview and missed important messages. The next version of the message system was improved such that message got a priority and in the user interface they are sorted according to this priority. Moreover, the messages can be selected by the supervisor and the user interface proposes a list of actions (e.g. add a snapshot, add a 3D-label). Even though message handling was made easier, suitable visualization of messages remains a major shortcoming in the interface. This will be one of the focus points in future work.

Relations between entities were normally fixed in the small teams, such that visualization was not needed. Similar, the representation of capabilities was not yet necessary for small teams. If complex tasks require larger, dynamic teams new features have to be implemented.

V. CONCLUSION

In this paper we have elaborated challenges for user interfaces in human-robot teams. User interface requirements have been shown for different roles the human can take in the team on the basis of three implementations. The presented work contributes towards a design guide for interfaces in joint human-robot teams.

Experimental evaluation has shown that the designed interfaces are useful for human-robot teams. Future work includes more user testing and appropriate improvements. New features will be developed and compared. Until now we have considered mainly information display, communication, as well as control and navigation. Further work is required to also make advance towards the other challenges.

Future research will also discuss the role of the robots in the team. It is still an open question, if robots can be equal team members and e.g. maybe one day decide themselves about task allocations. Finally, our future interest is to understand how human-robot teams can work efficiently together by incorporating their complementary capabilities into the team and how we can build systems to support efficient cooperation and interaction.

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