WEB-BASED INTERFACE DESIGN FOR TELEOPERATION

Dezhen Song and David B. Kaber
Mississippi State University
Mississippi State, MS 39762-9542

This article focuses on web-based teleoperation system design. We review current web-based telerobotic systems and identify human factors issues associated with them. Subsequently, the difficulties and challenges of interface design for web-based teleoperation are analyzed from the perspectives of system implementation and human factors. A prototyped web-based system was developed to further explore the design problems. An empirical study involving comparison of different prototype design options is described. On the basis of the research, several design guidelines were formulated for future work in this area.

INTRODUCTION

The World Wide Web (WWW) is one of the major components of the Internet and has promoted dramatic change in our living and working styles. The WWW eliminates traditional communication barriers such as long-distance, time constraints, and sometimes, language differences (i.e. if a graphical communication system is used). Therefore, the WWW provides us with a new working environment where people living in different places can work together collaboratively and efficiently given proper design of the environment.

These new technologies can be exploited not only for distributed communication but distributed command and control applications as well. Teleoperation tasks are usually complex jobs in which several experts in different fields are involved in collectively controlling a remote manipulation device to extend human perceptual, cognitive and motor-control capabilities into distant or inaccessible environments. Conventional teamwork requires that all team members or experts work at the same time and in the same place, which is usually difficult to arrange and increases job costs particularly if there are mission time constraints. With this in mind, in this research we attempted to create a web-based collaborative working environment for effective and economical control of a telerobot system. Based on a review of existing telerobots on the web from a human factors perspective, we focused on how to design a web environment or site to serve as a useful and usable interface to the telerobot. We perceived this research to potentially have broad web design implications associated with it as many dynamic web pages are currently being developed to act as user interfaces to real-remote systems including, for example, financial systems, travel reservation systems, etc. as part of e-commerce.

OVERIEW OF SYSTEMS

The dawn of the web-based telerobot occurred in 1994 when the University of Southern California placed a two-jointed manipulator on-line (Goldberg et al., 1995) [http://cwis.usc.edu/dept/garden/]. The telerobot system was designed to allow a user to view and tend a live garden, referred as the "telegarden". Just four weeks later, Australian robotics researchers connected an ASEA IRb-6 robot to the Internet and it has remained on-line since that time (Taylor & Trevelyan, 1995) [http://telerobot.mech.uwa.edu.au/]. Currently, there are no less than 15 telerobots that have been made accessible through the Internet allowing users to control them and perform a variety of tasks (e.g. picking and placing blocks, etc.). Web-based telerobot systems have become a popular area of web development research for computer scientists, mechanical engineers, and human factors professionals. Unfortunately, if one compares current web-based telerobot systems with those created approximately five years ago, you find that there has been no significant change or improvement in terms of functionality or interface design, as well as applications. Most systems have been designed only to satisfy user curiosity and for the purposes of entertainment. As noted, systems have been designed to perform experimental tasks including picking-and-placing blocks, however, no commercial teleoperation or potentially commercial uses of web-based telerobotic systems have been formulated.

We believe this is due to human factors issues in the design of dynamic web-pages to serve as effective interfaces to on-line telerobots, as many novel and meaningful applications of web-based telerobotics have been formulated. These include developing Common Gateway Interface (CGI) and Java based web-pages to serve as shared-control interfaces of a telerobotic system. Human factors issues relevant to web-based telerobot interface design must be resolved before any applied research can move forward into advanced application deployment. To identify human factors design issues in web-based telerobot systems, we reviewed the majority of systems currently on-line including Carnegie Mellon's web-robot [http://www.cs.cmu.edu/afs/cs.cmu.edu/Web/People/Xavier/], etc. In general, these systems have not been adequately explored by human factors professionals. For example, according to models and frameworks of human-computer interaction, the interface should serve to bridge any gaps between the psychological goals of operators and the physical state of the telerobotic system (Norman, 1986). Unfortunately, due to the complexity of telerobotic systems and limitations of design in web-based interface development, these gaps have been more difficult to bridge than in, for example, desktop computing application interface design. Designing a good interface for a web-based telerobot may be more challenging and require more effort.

INTERFACE DESIGN CHALLENGES

Design challenges that need to be addressed in current web-based telerobot systems include providing feedback to users on the state of a teleoperator and intuitive control devices, and ensuring control-display compatibility. Some of these challenges are related to human information processing capabilities. For example, humans in control of teleoperators are usually poor at translating manipulator position coordinates to a corresponding location in real space, as presented through an interface and video display terminal. Therefore, an operator's ability to project future system states may be limited if the system interface is strictly text-based. Specifically, they may not be able to comprehend the position of a manipulator or project a future goal of the system. Consequently, graphical feedback may be necessary when designing such interfaces. However, there are also design challenges associated with graphical feedback that emanate from limitations of the Internet and Internet technologies in terms of bandwidth and data communication speed. It is standard practice to provide video feedback on manipulator systems as part of teleoperator control interfaces. Based on current teleconferencing technology, the design strategy for web-based systems is to incorporate live-streaming video in a dynamic web page. This method can provide live video of a remote manipulator system, but frame rates are usually limited to 10-15 frame/sec. Furthermore, frame rates can fluctuate dramatically over short periods of time due to fluctuations in the speed of the Internet because of communication load. This can be a critical issue in web-based teleoperation because no matter how good the graphical feedback (video quality/resolution), if it is not provided in a timely manner, operator system awareness and control will be compromised. Feedback latencies may make it very difficult for operators to maintain adequate situation awareness for system state projection and performance may suffer. Although it may be possible for high frame rates (15-30 frames/sec.) to be achieved using live-streaming video through the web, these rates currently only come at the expense of the resolution of the video. The typical highest resolution of a teleconferencing protocol is approximately 320 by 240 pixels, which is insufficient to serve as detailed graphical feedback for a real-world teleoperation task (e.g. a pick and place task involving ordinaces or hazardous waste materials). An additional problem associated with using live-streaming video in web-based teleoperation is that synchronizing the delivery of video to multiple users simultaneously is virtually impossible. This poses a serious problem for advanced teleoperation applications involving a team of experts working together through the Internet to effectively control a telerobot. If the graphical feedback being transmitted to the experts is not synchronized, the ability of the team to develop shared system and situation awareness critical to coordination may be compromised.

Aside from human information processing limitations and limitations of the capabilities of the Internet impacting how teleoperator interfaces should be designed to convey system states, human motor-control capabilities may also be related to teleoperator design challenges. For example, advanced, multi-degree-of-freedom robotic arms normally have more joints than the human arm and, therefore, the motor-control capabilities and kinematics of such devices are beyond human operator expectations and comprehension, which is based on the dexterity achievable with the human arm. This may pose a serious difficulty for operators in translating motion objectives into control actions and actually controlling the robot. This problem can be addressed by incorporating simplified or goal-oriented modes of control into teleoperation system interfaces. For example, world-mode control prividing automated translation of control commands into precise movements of multiple joints can dramatically reduce the cognitive complexity of teleoperation involving joint-by-joint control of a manipulator. Since users of world-mode control rely only on a three-dimensional (3D) coordinate system associated with the robot end-effector for motion planning instead of needing to understand robot kinetic properties, their mental workload may be significantly reduced.

The third major design challenge we identified to be associated with web-based teleoperation system interfaces is driven to some extent by both human information processing and motor-control capabilities and limitations. Ensuring that user control actions using interfaces such as Spaceballs®, joysticks or virtual controls (e.g. push-buttons included on a visual display selected using a mouse to cause robot motion) are compatible with the resulting motion of the manipulator system is critical to overall performance. To ensure that users of web-based robots obtain linear depth cues from two dimensional (2D) views of a manipulator and task objects, many sites provide multiple viewpoints. Virtual controls are usually incorporated in sites as part of a control panel resembling a traditional robot teach pendant. Buttons are used to drive a manipulator motion along one of three coordinate axes. Textual descriptions are often used to identify the functions of a button. For example, a button marked "X+" may mean the robot manipulator will move laterally to the right along its X-axis in the user's field of view if the button is clicked. Therefore, the control panel would consist of six buttons to implement 3D control of the manipulator. The control-display compatibility problem with this type of setup is that the direction of robot motion caused by each button on the control panel does not change while the user's viewpoint of the manipulator may. Consequently, the behavior of the robot, as viewed through a particular 2D display, may not correspond with a user's expectation of their control actions based on experience with another display. For example, the "X+" control button causes a rightward motion of the arm in a front view, but a rearward motion in a left-side view. Incompatibilities between controls and displays, like this, place an extra cognitive load on users by requiring them to continuously transform their mental motor-control maps during teleoperations as a result of using different viewpoints to gain perspective on a manipulator.

A final issue associated with control/display compatibility stems from the use of dynamic viewpoints in teleoperator visual interfaces (web-based or traditional). To provide a clear view of operation, some web-based teleoperation interfaces incorporate the capability to control camera viewpoints in their system design. Users are provided with functions to control both camera direction and camera zoom. Changing the direction of a camera can lead to the control/display misalignment problems discussed previously. However, the problem becomes more complex if the zoom is adjusted as well. The effect of changing the camera's zoom is similar to adjusting the gain of a hand controller for conveying manipulator motion, but it is fundamentally different. Zooming the camera in on an object appears to amplify the control effects and vice versa, which looks like a change in control gain. However, in actuality, the control action is the same, the view of the workspace is simply magnified. Dynamic changes in a camera's zoom can cause the amplitude of control gain to appear dynamic. Under these circumstances, users may unwittingly seek to adjust the amplitude of their control actions to compensate for the virtual changes in control/display gain. Consequently, zooming a camera in on the robot often causes undershooting of positional goals and zooming out usually creates over-shooting through control actions. Like dynamic viewpoints, the capability to zoom can create an extra mental workload for humans when performing teleoperation tasks in attempting to dealing with false gain changes.

PROTOTYPE SYSTEM DESIGN AND EVALUATION

On the basis of our investigation of teleoperator interface design challenges, we designed and prototyped a web-based system using a high performance graphics workstation and an industrial-grade robot (PUMA 560) to support a research program aimed at establishing design guidelines for useful and usable web-based teleoperator interfaces. Our overall objective for this research was to encourage the use of the web as a mechanism for shared control of telerobots in novel real-world applications. Unique features of this system that were developed by considering some of the above design challenges in system feedback mechanisms include diagrams of the telerobot in the visual interface associating 3D coordinates of manipulator positions with pictures of actual locations of the robot. The reference diagrams present sample position pictures with an annotated manipulator coordinate system and joint coordinates (see Figure 1). They are aimed at promoting operator awareness of telerobot system states. The interface also provides near real-time graphics and textual feedback on telemanipulator positions towards maintaining operator system awareness. Dynamic 2D images of the robot component of the system are used as graphical feedback on manipulator status. The images are high-speed snapshots of the telerobot transmitted across the web from closed-circuit cameras to a web-server. This approach is in lieu of live-streaming video, which may pose high network communication loads and inhibit the overall responsiveness of the system. These images are updated at regular intervals. The update rate is determined by the connection speed of the Internet and the communication bandwidth requirements associated with graphical feedback. More specifically, the size and resolution of the images dictates the bandwidth requirements and, consequently, the update rate. The viewpoints of the manipulator provided through the dynamic image feedback are identical to the viewpoints presented in reference diagrams in order to ensure operational compatibility.

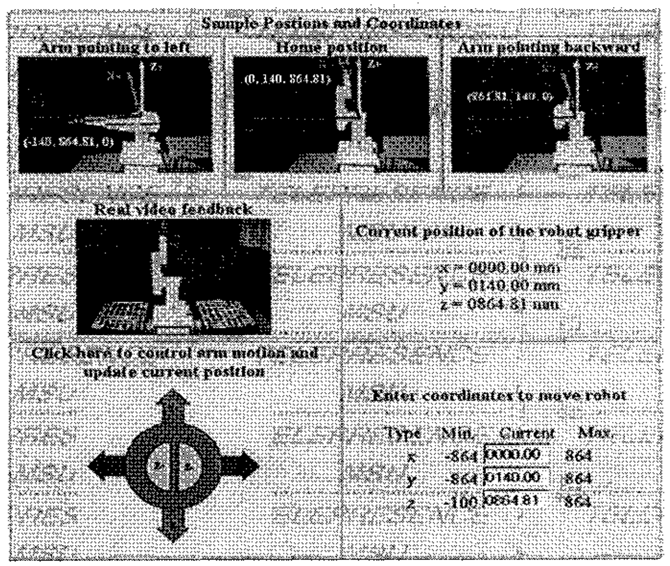

Figure 1. Prototype design of web-based teleoperation system (http://www2.ie.msstate.edu/wcr).

In terms of interface controls, the prototype system provides virtual controls (push-buttons as part of the visual interface) for remotely changing the position of the robot along a specific axis of motion. The interface also allows for text input of manipulator positional goals through an input dialog box. The push-buttons are arranged in a fixed-position control panel and facilitate world-mode control of the telerobot. Experienced users can enter 3D destination coordinates directly through the dialog box while novices may prefer to the use virtual controls on the graphical control panel to change the telerobot's gripper position.

The labeling of the graphical control panel and buttons is compatible with the 3D coordinate system presented in the reference diagrams and dynamic image feedback to enable operators to project the direction of manipulator movement resulting from selecting a particular control button. In the near future, a Java-based 3D or Virtual Reality Modeling Language (VRML) model of the robotic component of the system is to be incorporated into the web interface to provide operators with an enhanced capability to preview control actions. This model should serve to improve operator system awareness, specifically the projection of system states in the future, and mental model development describing system behavior associated with particular control actions. The model will also directly support system performance by allowing operators to verify the accuracy and safety of control actions in advance of actually executing them. For example, when a user inputs a command, the Java-based 3D or VRML model will be activated to simulate the telerobot action caused by that command and will allow the operator to determine whether the move is acceptable. The model will be strictly based on the kinetic properties of the PUMA 560 robot to ensure the validity of the preview display with respect to the real robot action/motion. Aside from providing a preview of the effect of current and future commands on telerobot performance, the model can also be used to present the current robot position and it can be used to recreate historical robot motion sequences simply by using a log of manipulator coordinates previously fedback to the user. This may ultimately help users perceive and understand various system states.

To address the design challenge of control/display compatibility, we conducted an experiment to compare the usefulness and usability of four different visual display and virtual control combinations as part of a prototype dynamic web page for telerobot control. Not surprisingly, the results of the experiment revealed that people who used the control panels that were compatible with displays significantly outperformed those using incompatible controls and displays in specifying the correct motion commands to accomplish pick-and-place tasks. There was no effect of display condition on performance.

DESIGN GUIDELINES

Based on our review and analysis of current web-based telerobot systems, experience in prototyping a system and evaluating its design in terms of teleoperation performance, we formulated several design guidelines that we urge roboticists, engineers, etc. to take into consideration when designing similar systems. These guidelines include:

- providing users with an operating frame of reference, such as system diagrams showing prototypical states and system variable values;
- ensuring a user's frame of reference for controlling a manipulator is compatible with graphical feedback on the system;
- incorporating graphical feedback into web interface design including dynamic images, which may be preferable to live-streaming video due to limitations in Internet bandwidth and communication speed;
- using only translational control as a control strategy to reduce the cognitive load on operators associated with translating control intentions into actions under rotational control modes in the absence of automation to make robot kinematic considerations;
- incorporating virtual control panels and text input-boxes into the interface to accommodate both expert and novice users;
- considering spatial and operational compatibility in display and virtual control design;
- for system providing only a single viewpoint of a robot, a 3D control panel with functions compatible with displayed robot motion is sufficient;
- for systems providing multiple viewpoints of a manipulator, a 2D control panel with functionality that changes depending upon the displayed viewpoint is a superior design option to ensure control/display compatibility;
- incorporating a control algorithm in the system that automatically adjusts control gain to compensate for changes in viewing camera zoom;
- incorporating multiple viewpoints of a robot into the web page to aid users in constructing a 3D mental picture of the system and perceiving linear depth cues (e.g., perspective, interposition, etc.); and
- providing a 3D virtual simulation of the robotic component in the web interface to allow users to preview motion commands and accurately project future system states.

DISCUSSION

Using the Internet as means for communication, and systems command and control tasks, shows great promise for work efficiency and economy in comparison to traditional methods of distributed communication. This is primarily due to human travel time and costs. Current barriers to effective web-based collaborative working environments for teleoperations are related to human information processing and motor control capabilities, and include effective web-based interface design and Internet communications capacity and speed. Our current efforts are aimed at developing specific guidelines for web-based telerobot system design to overcome these existing problems. In this paper, we have provided some more obvious recommendations to promote the usability of existing and future system interfaces. It is our hope that this type of human factors research and future studies will serve to effectively advance the application of web-based environments for telerobot applications including space and undersea science. In general, this research may be important to ensuring the proper design of web-based environments and interfaces for supporting everyday human activities involving complex systems (e.g., banking, grocery shopping, etc.), improving usefulness and usability of these interfaces, and facilitating situation awareness in electronic environments for effective performance.

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