Interface evaluation for soft robotic manipulators
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ABSTRACT
This paper reports the results of a usability experiment evaluating a human interface for the operation of a soft robotic manipulator (OCTOR), a biologically inspired robot arm modeled after octopus tentacles. Such “continuum” robotic limbs provide unique challenges due to the nature of their movements because they are not intuitive to humans and due to the many degrees of freedom for the operator to control. Two modes have been developed to control the arm and reduce the degrees of freedom under the explicit direction of the operator. In coupled velocity (CV) mode, a joystick controls changes in arm curvature. In end-effector (EE) mode, a joystick controls the arm by moving the position of an endpoint along a straight line. In the experiment, participants used the two modes to grasp objects placed at different locations in a virtual reality simulation (VRML). Objective measures of performance and subjective preferences were recorded. Results show lower grasp times and a subjective preference for the CV mode. Recommendations for improving the interface included providing additional feedback and implementation of an error recovery function. The results of the tests serve as a guide to designing interfaces for a wide array of soft robotic manipulators.

Author Keywords
Robot control, interface design, usability

ACM Classification Keywords
H5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION
Two usability experiments were conducted to evaluate the human interface for the operation of a soft robotic manipulator (OCTOR), a biologically inspired robot arm modeled after an octopus tentacle. OCTOR is a “continuum” robotic arm which allows it to pivot at virtually any point along its length. This is in stark contrast to typical robotic arms which consist of a finite number of pivots, usually less than five. This ability serves as a double edged sword. It affords movements and capabilities that were never possible with a traditional robotic arm. At the same time the maneuverability serves as an overwhelming task for an operator trying to control the arm. Therefore, if the operator interface is poorly designed the arm’s potential could be lost.

The OCTOR arm is pneumatically driven arm comprised of three sections, each containing three pneumatic lines or “muscles.” These lines can be pressurized or depressurized in order to make the arm move. The arm had been designed to attach to a small unmanned ground vehicle (UGV) such as the Foster-Miller TALON, see Figure 1. The mounting of the arm to an UGV allows the operator to enter a hazardous environment and manipulate objects while remaining at a safe distance. In addition to the degrees of freedom (DOF) afforded by the three sections there is also a motor at the base of the arm which allows the arm to be rotated. However this was not examined in either of the following studies.

Figure 1. The OctArm robotic limb attached to the Foster-Miller TALON.

In the field an operator uses a combination of the camera views from the TALON coupled with a virtual reality (VR) display of the arm in order to maneuver the arm and
manipulate objects. A screenshot of the VR interface can be seen in Figure 2. The three sections multiplied by the three “muscles” per section creates the possibility for 9 separate control inputs. The use of 9 independent control inputs would easily overload an operator even after extensive practice. The use of synergies between these 9 input channels would therefore reduce the cognitive workload on the operator. Thus, rather than using a control device with 9 separate knobs or sliders to control each muscle, a Logitech® Extreme™ 3D Pro joystick is used as the input device. Two different synergies were developed to control the arm. Two modes, Coupled Velocity (CV) and End-Effector Mode (EE), were developed to control the arm and allow the number of DOF to be reduced subsequently reducing operator workload. CV mode is a 0th order control mode that allows the user to select one or more of the three segments and with the amount of curvature being specified by the amount that the joystick is moved. In EE, a synergy is created by linking joystick motion to the movement of the lowest active point of the arm. Thus the operator could move the endpoint along a straight line with the curvatures of the arm being adjusted automatically. Two experiments were conducted in order to ascertain the strengths and weakness of each mode as well as to make recommendations for improving the interface.

METHODS
Participants
Five female undergraduate students participated in the experiment after providing informed consent. They were monetarily compensated for their time.

Experimental design
A mixed factorial design was used. Each participant completed two sessions, one per control mode. Each session consisted of 8 trials. Three of the participants had CV mode first, while the other two had EE mode first. Each trial required the participant to maneuver the arm in order to grasp a sphere placed in the VR environment.

Experimental procedure
The participants were instructed to grasp the sphere as if it were a real object that they were going to pick up with the actual arm. The participants were shown Figure 3 to define a “Good” grasp and Figure 4 to define a “Mediocre” or 2-point grasp. They were instructed to grasp the object securely, but quickly, and to avoid accidentally contacting the sphere. Each session began with training on the controls of the arm. The function of each button was explained to the participant and they then practiced that function. After all of the functions had been explained the participant was then allowed to practice maneuvering the arm without any spheres present. Once the participant felt comfortable the first trial began. The training and practice lasted on average between 10-15 minutes.
shortening the arm defined the difficulty level. Thus, the first trial only required the participant to move the arm in one plane and then pull the trigger to make a grasp, while later trials required the participant to move the arm in all three planes and then lengthen the arm in order to grasp the sphere. During each trial of the experiment, participants were asked to speak aloud and provide verbal protocols regarding the strategies, frustrations, and thought processes involved with their actions in completing the task of grasping a virtual sphere in black space. These comments were documented by the experimenters via laptop or handwritten notes and then compiled into a document for each participant for analysis. The experimenter noted any incongruence in attempted actions and the actual resulting actions. At the end of the second session the participants were given a subjective questionnaire to rate and discuss each mode.

RESULTS AND DISCUSSION

Trials 1 and 2 were considered to be practice trials and were therefore excluded from data analysis. A single trial by one participant was determined to be an outlier (±3.0 SD for time to complete) and was removed from the data set. The average grasp time between modes was not significantly different between CV (m = 681.6s) and EE (m = 759.97s), F (1,56)= .346. Figure 5 shows the average grasp time broken down by session and control mode.

Despite the fact that grasp difficulty increased progressively from Trial 3 to Trial 8, the average grasp time did not increase consistently across trials. For trials 3-8, F(5,52) = 1.839. This is likely due to the fact that participants were learning how to more efficiently maneuver the arm as the trials progressed and their increasing skill level cancelled out the increasing difficulty level. Figure 6 shows the average grasp time per trial.

Despite the lack of a statistically significant difference in average time between modes, the subjective data showed that the participants had a very strong preference for CV mode. CV mode was preferred by four of the five participants despite the fact that more people (3) had CV as the first mode, which would seem to put that mode at a disadvantage in terms of user experience. It was expected that the first mode tested would be less preferred due to learning of participants from the first session to the second.

RECOMMENDATIONS

The experiment yielded a great wealth of design recommendations. Based upon the user feedback and the experimenter’s observations of participant performance, five key design recommendations were made. The first recommendation was to add the capability to undo or “backup” the arm. This recommendation resulted from numerous participants maneuvering the arm up to the sphere and then accidentally drastically moving the arm causing them to have to spend a significant amount of time re-maneuvering the arm back to where it was before the accident. The second recommendation concerned the autograsping function, which caused the most distal section of the arm to automatically curl into a grasp. The speed of the autograsping was set to occur at the same rate as the current setting for whole arm movements. The recommendation was made to have the autograsping speed remain fixed regardless of the entire arm’s speed. The third recommendation was to provide more user feedback concerning the length and curvature of the arm. Participants were unsure when the arm had reached its maximum or minimum length or curvature. Many participants were also unclear of the relation of length and curvature and its effect on movement limitations in EE mode. The fourth recommendation concerned the ability of the operators to orient themselves in the virtual environment when the viewpoint had been changed from the “Home” or original view. When the viewpoint had been changed from the “Home” view, the movements of the joystick no longer
mapped the same way as they did while at the “Home” view. The addition of color-coded arrows to the VR arm along with corresponding color-coded tape on the base of the joystick was recommended to keep the operator oriented to the rotated arm. This color-coding would also be beneficial when in the “Home” view. The last design recommendation concerned the ability to practice a movement in the VR environment prior to making a movement with the actual OctArm.

In addition to testing the current system interface another avenue of testing would be to utilize a direct manipulation control to interact with the same VRML display. A direct manipulation control would allow the operator to use a mouse to click on a point on the arm and drag that point to reconfigure the arm. This control system would help to alleviate some of the problems in the current control system, but would not address other problems.

A direct manipulation interface would alleviate much of the ambiguousness in orienting when in a different view from the home view during testing using only the VRML environment. However, until an interface is devised that can integrate the real-world view from the cameras and the VRML display of the arm the full benefits may not be repeated. The addition of such features as increased feedback and the undo function could be as easily added to a direct manipulation control as it can be to the current system.

Other non-usability methods to improve operator performance are currently being investigated. These methods include prescreening of operators for spatial cognitive abilities. Despite even the best prescreening for the best spatial abilities, the interface must be usable and therefore more iterations of the interface will be conducted.

CONCLUSION
The results of usability experiments, such as those presented here, provide valuable information that can be used by designers to understand how a given system will function under actual use. This is paramount for complex interfaces. Such experiments reveal information that is typically not uncovered by designers during routine testing outside of formal usability experimentation. The result is a final product that can be operated more efficiently with fewer errors and with increased safety.

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REFERENCES