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7. Abstract

This report describes the usability testing that has been done for the control and data acquisition system for the Light Duty Utility Arm (LDUA) System. A program of usability testing has been established as a part of a process for making the LDUA as easy to use as possible. This report covers the first stage of usability testing, which focused on human machine interface (HMI) issues involved in teleoperation (human-in-the-loop) of the LDUA arm and mast in joint mode using a animated 3-D graphic simulation of the arm and its operating environment. Video camera views were also simulated because they will be an important constraint on teleoperation.

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USABILITY TESTING OF THE HUMAN-MACHINE INTERFACE

FOR

THE LIGHT DUTY UTILITY ARM SYSTEM

Revision 0
September 10, 1994

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USABILITY TESTING OF THE HUMAN-MACHINE INTERFACE FOR THE LIGHT DUTY UTILITY ARM SYSTEM

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USABILITY TESTING OF THE HUMAN-MACHINE INTERFACE FOR THE LIGHT DUTY UTILITY ARM SYSTEM

1.0 INTRODUCTION

1.1 PURPOSE

This report describes the usability testing that has been done for the control and data acquisition system for the Light Duty Utility Arm (LDUA)[1] System. A program of usability testing has been established as a part of a process for making the LDUA as easy to use as possible.

1.2 SCOPE

This report covers the first stage of usability testing, which focused on human machine interface (HMI) issues involved in teleoperation (human-in-the-loop) of the LDUA arm and mast in joint mode using a animated 3-D graphic simulation of the arm and its operating environment. Video camera views were also simulated because they will be an important constraint on teleoperation.

1.3 SUMMARY OF RESULTS

This work resulted in the identification of several important improvements to the LDUA control and data acquisition system before the design was frozen. The most important of these were color coding of joints in motion, simultaneous operator control of multiple joints, and changes to the field-of-views of the camera lenses for the robot and other camera systems.

1.4 OVERVIEW OF THE LDUA SYSTEM

The LDUA System is being designed to deploy a family of tools, called End Effectors, into underground storage tanks by means of a robotic arm on the end of a telescoping mast, and to collect and manage the data that they generate. The LDUA System uses a vertical positioning mast, referred to simply as the mast, to lower the arm into a tank through an existing 30.5 cm (12 in.) access riser. A Mobile Deployment Subsystem is used to position the mast and arm over a tank riser for deployment, and to transport them from tank to tank. The LDUA System has many ancillary subsystems including the Operations Control Trailer, the Tank Riser Interface and Confinement Subsystem, the Decontamination Subsystem, and the End Effector Exchange Subsystem. The LDUA

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[1] The Light Duty Utility Arm (LDUA) System is being developed under the sponsorship of the Underground Storage Tank Integrated Demonstration Program (UST-ID) of the DOE Office of Technology Development (DOE-OTD).

is being designed to operate safely in the hazardous (high radiation, flammable gasses, corrosive chemicals) environment typical of the 177 underground storage tanks at the Hanford site and underground storage tanks located at other DOE sites.

The LDUA system is designed to be operated from the remote Operations Control Trailer located outside the perimeter fence of the tank farm, up to 275-m (900-ft) from the deployment vehicle.

2.0 USABILITY TESTING

2.1 REASONS FOR USABILITY TESTING

Improvement of the LDUA HMI will be an iterative process of making changes based on feedback coming from the users through usability testing. As with all remotely controlled systems, design of the LDUA HMI must deal with two primary issues: how to best convey information about the robot and its environment to the operator, and how to best convey the operator's desires and commands to the robot. How well these two areas are dealt with determines the usability of the system. Even if a tool is suited for its task, if the interface has been poorly designed, it will be viewed as an impediment. End users are unimpressed by technology for its own sake and the system will be judged strictly on the basis of how easy or difficult it makes their job. A good interface invites its users, encourages them to master its operation, and ultimately makes them and the system more efficient. A poor interface has quite the opposite effect.

2.2 DESCRIPTION OF USABILITY TESTING PROCESS

The process of usability testing involves bringing in users, sitting them down in front of the simulator, and then asking them to carry out specific, predetermined tasks. These tasks take the form of "Provide a close-up examination of the underside of the center 42" riser.", or "Scan the tank wall surface looking for faults in the welds." The user is left to struggle with the task and carefully observed by the test administrator. The test administrator's job is to try to understand, and where necessary to extract, the user's *expectations* of the system. To this end, a "thinking out loud protocol" is frequently used. A thinking out loud protocol means having the user speak his thoughts out loud during the process of carrying out tasks; to actually have the users explain their intentions and expectations during the task performance.

What is being tested is the interface, not the user. In general, the user is left to attempt tasks alone and a question like "How do I move the shoulder yaw joint?" is answered by the test administrator with another question "How do you think you should be able to move the shoulder yaw joint?". If a user is forced to *think* about *how* to do something, this indicative of problems with the HMI. Sections of the interface that receive no comment, or are unnoticed by the user, are in fact the most usable sections of the interface. An ideal interface is one that is transparent to the user. In other words, the goal of usability testing is to make operating the LDUA obvious to the user, not through extensive training, but by designing an *intuitive* interface.

Bringing in users who are unfamiliar with the system forces one to have answer the most basic and obvious questions (such as "How do I turn it on?", or "What is that I am doing right now?"). Questions that expert users wouldn't even think to ask. The designers of a system are generally the worst people to use for usability testing because everything is obvious to them.

There are no formal statistics associated with the results of this testing. Statistical analysis is not the goal of usability testing; something either works or it doesn't. While designed experiments used in scientific analysis must be concerned with sample sizes and probabilities, significance in usability testing requires only one user to ask "Did I just send the arm through the tank wall? I can't tell." to indicate an HMI problem.

Informal usability testing was conducted using non-operators such as other engineers, student interns, and secretaries because access to actual tank farm operators was limited to only a few sessions. Such informal tests were beneficial as quick screenings on specific portions of the interface to eliminate bad or weak features, or to assess whether changes in the interface actually improved the problem they were intended to solve. More formal testing was done with the actual tank farm operators. This testing used scripts and questionnaires to insure consistency and completeness. Sessions were videotaped and notes taken. A more thorough analysis of the details of the interface, and its gestalt, was therefore possible.

3.0 ESTABLISHING TESTING DOMAIN

Before usability testing could begin the following issues needed to be decided upon:

- an understanding of tasks that user must perform
- an understanding of who are the users and their what are their expectations
- a selection of components of the LDUA HMI to test

3.1 TASK ANALYSIS

To test whether something is usable requires an understanding of what it is to be used for. A top level task analysis (Appendix A) was prepared for all LDUA missions that were planned or envisioned including the initial hot deployment (mission 1), and subsequent deployments. Only Mission 1 of the LDUA had a firm budget and scope, therefore usability testing was limited only to include proposed Mission 1 tasks. Meetings with Tank Farm Operations and reviews of previous tank surveillance video tapes helped to break down all Mission 1 tasks into the following two classifications:

<u>survey tasks</u>- These tasks involve exploring into areas which are unknown. The main goal consists of *identifying points of interest*, which are defined as any characteristics of the tank which are different than the rest of the tank. Performance of these tasks involve a combination of search patterns and obstacle avoidance. *For survey tasks, the HMI must allow the operator the capability to operate the LDUA such that no area is overlooked and all collisions with the tank environment are avoided*

<u>examination tasks</u>- These tasks come after a survey task has been completed and further information is desired. Another possibility is that the location of the point of interest is already known from earlier photos. The main goal for examination tasks consists of *positioning the end effector in a configuration such that additional information about a point of interest can be obtained.* Performance of these tasks involve a combination of goal seeking and obstacle avoidance. *The HMI must allow the operator to achieve the desired configurations while avoiding all possible tank collisions.*

3.2 USERS

Thorough usability testing means working closely with the end users and having an understanding of their needs and expectations. The LDUA system will be operated by Hanford Tank Farm Operators. These operators are not degreed technologists, but are skilled workers who will receive specialized LDUA training. A kickoff meeting was held with the operations organization that would be responsible for operating the LDUA in order to explain the process and to discover their expectations and goals for the system. The operators appear to have few specific expectations of the system since the LDUA is unlike any other piece of equipment they are familiar with using. No particular template design for the LDUA HMI exists, but the operators indicated that they were open and willing to learn new systems. Operators are also not computer experts, but it was determined that they would at least be comfortable with the idea of computer-based systems. It is not necessary that the LDUA interfaces be designed so that all tank farm operators could qualify as LDUA operators.

3.3 SELECTION OF INTERFACE COMPONENTS FOR TESTING

The LDUA control and data acquisition system is designed to be run by two operators; a data acquisitions operator responsible for collecting data from various end effector tools and sensors, and an arm operator responsible for manipulating the arm. These operators use computer workstations provided by the LDUA control and data acquisition system; the arm operator uses the Operations Workstation and LDUA Console, and data acquisition operator uses Data Acquisition Workstation.

The Operations Workstation provides a 3-D animated graphic display for visualizing the operation of the mast and arm. The operator may preview motion of the arm in simulation using any of the motion control modes that the system provides (teleoperation and automated path following). If the motion is acceptable and collision-free, the operator is given the option of having the system execute the motion as it was simulated. The 3-D animation capabilities of the Operations Workstation are provided by the commercial software package IGRIP[2] (Interactive Graphic Robotics Instruction Program) .

The LDUA Console works in conjunction with the Operations Workstation. It provides display and access to the detailed status and operating parameters of the mast and arm controller. The LDUA Console is directly connected to the robot controller and is therefore capable of operating as an independent backup, if necessary, to the Operations Workstation. Hand controllers (such as joysticks) are connected to the LDUA Console for teleoperation of the mast and arm.

The Data Acquisition Workstation provides the primary user interface for operating End Effectors, collecting data, and for monitoring and controlling the TRIC environment subsystems. It provides a single point from which data can be acquired, processed, and stored. It is based on the commercial software package Labview[3], which provides a rich set of instrumentation display tools.

There are many video cameras in the LDUA System for observing operations, including units on the arm, in the tank, and in the ancillary equipment. The video display and recording subsystem provides monitors and VCRs to display and record video information from these cameras. All aspects of video switching and display and recording are controlled by the Data Acquisition Workstation, including the video cameras, the routing of signals, the VCRS, and the overlay of titles and other selected information onto the video.

The Auxiliary Workstation provides the ability to obtain information from the system without disturbing the operators at the primary workstations. It is located in the rear area of the Operations Control Trailer away from the operating area. Printers, plotters, and other peripheral devices are also located in this area.

The decision was made to focus the first stage of usability testing on the Operations Workstation and postpone the Data Acquisition Workstation, and the very interesting area of interaction between the two operators. This was principally because of limitations of time and resource and the desire to keep the first effort small enough to insure an initial success with the testing program.

4.0 THE ARM CONTROLLER SIMULATOR

The next step in the process was the design and construction of the simulation that the operators would use. The actual Operations Workstation computer and the IGRIP software package were available for this purpose. It was decided that the simulation would include:

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[2] "IGRIP" is a trademark of Deneb Robotics Inc.

[3] "Labview" is a trademark of National Instruments Inc.

- Tank environment
- Mast and Arm animation
- Camera views and controls
- Joysticks

4.1 WORLD MODEL

The tank environment and the mast and arm animation will make up what is known as the "World Model" in the actual Operations Workstation. The World Model will allow the motions of the mast and arm to be previewed as a simulation and checked for correctness and freedom from collisions before actually moving the arm.

4.1.1 Tank Environment

The model of the tank environment is based on best existing knowledge of the tank. For the simulator, underground storage tank 241-A-105 was modeled, which at the time was the proposed tank the LDUA would first be deployed in. The goal was to make the model to a resolution of one half inch, to be as accurate as possible, and to include details of the tank internal structure such as risers, pump wells, wall stiffeners, and weld seams. Simulated points of interest were added to the World Model in the form of cracks, splotches, and holes. These points of interest were not necessarily representative of actual features in the tank, but were necessary in order to provide operators with targets for their simulated tasks.

If all the information about the tank and its internal structures are available, an expert IGRIP operator can create an accurate model of the tank environment in about two days. Unfortunately, getting all the information about a tank is the hardest part of generating the World Model. Many of the tanks are over 50 years old and may have been modified from their original drawings. The total number of polygons needed to generate the 241-A-105 tank (the number of separate shapes that the graphics computer has to render), is about 5000.

4.1.2 Mast and Arm

The manufacturer of the LDUA furnished a detailed, dimensionally accurate, and correctly articulated IGRIP model of the arm to WHC. The arm has seven rotational joints (shoulder yaw, shoulder pitch, upper elbow yaw, lower elbow yaw, wrist yaw, wrist pitch, and wrist roll), and is attached to a telescoping mast which essentially constitutes an eighth translational joint. The actual LDUA control system allows the operator to move the mast and arm in both joint space and cartesian space (resolved motion), using both teleoperation and automated sequences. Cartesian motions can be with respect to the tool frame of the End Effector or with respect to the world coordinate system of the tank. The mast can be selectively included or excluded in cartesian motions.

Cartesian motion of the mast and arm was not practical in the simulation during the first stage of usability testing because the inverse kinematics for them were unavailable. For a robot, moving in cartesian space involves calculating the inverse kinematics, which are the set of joint values necessary to attain a particular position and orientation of the robot's wrist or the tool it carries. Well known standard algorithms exist for robots that have as many as 6 joints, but solutions for robots that have more than six joints are unique to each robot and typically require an expert's knowledge to construct. IGRIP, as part of its standard package, provides only the standard inverse kinematics solutions. Some preliminary experiments were undertaken in operating the mast and arm in cartesian space using only the last six joints (shoulder pitch through wrist roll), essentially excluding the mast and shoulder yaw joint from the inverse kinematic calculations. However, the workspace of the resulting 6 joint LDUA was too limited to perform any useful operator tasks. The manufacturer of the LDUA will deliver a simulated controller for IGRIP that will perform the inverse kinematic calculations for 7 and 8 degree axis resolved motion by the end of calendar year 1994. At that time, usability testing with cartesian motion could be undertaken.

The first stage of usability testing was therefore conducted using teleoperation of the mast and arm in joint space - it was decided to postpone implementation of any automated sequences because of limited resources and the desire to keep the initial usability testing effort focused. Although joint space is only one of the methods that will be available to the operator in the actual LDUA control system, it is the most fundamental method and is an appropriate starting point.

4.2 CAMERA VIEWS

When the real LDUA is actually operating inside a tank, the operator will be able to directly observe the process using one or more video cameras. It was decided that simulating these camera views would be essential to providing a realistic teleoperation scenario. This simulation would also allow the camera design parameters to be evaluated.

Three camera views are modeled in the simulator; the LDUA shoulder camera which is located between the shoulder yaw and should pitch joints, the end effector camera which is carried on the end of the arm, and the overview camera which is deployed down a separate 10 cm (4 inch) access riser. Every attempt was made to make these models accurate with respect to camera and lens specifications (image plane size, focal length, zoom ratio, field of view) and camera pointing capabilities (pan and tilt). In the real LDUA system, three television monitors are provided to display selected camera views and the lenses and camera pointing are controlled from the Data Acquisition Workstation. In the simulator, however, the camera views and control panels are shown in split screen with each other and with the World Model view. The simulation allows the operator to decide how to split the screen and what views to display in which split. This approximates the video switching capability of the actual LDUA. In the simulator, however, unlike the real system, no discrepancies between the World Model and the camera views can ever exist.

4.3 JOYSTICKS

The LDUA manufacturer has chosen to provide two 3-axis joysticks for teleoperation. The rationale for this choice is that one joystick will control the translation axes in cartesian motion, and the other will control orientation. In joint motion, the manufacturer proposed that only one joint be active at a time and therefor only one joystick axis.

A pair of these joysticks (made by P-Q Controls, Inc.) were connected to the Operations Workstation through a BG Systems "CeralBox" converter, which translates the analog voltages produced by the joysticks into a serial ASCII data stream. The joysticks were mounted into a box 10 inches apart and placed at desk height. Because the box could not be mounted flush with the desk surface, the height of the joysticks was judged to be about 10 cm (4") higher than optimal.

4.4 OTHER CONTROLS

Except for the joysticks, all other operator controls in the simulation were provided by mouse activated button and menu constructs provided by the Graphic Simulation Language (GSL) of IGRIP. Programs written in GSL defined the specific buttons and menus for such functions as camera pan and tilt and switching the camera views. GSL code, while time consuming to write, is modular. Once the code has been written for any particular device (camera, robot, etc...) it is easily transferrable to other similar parts of the simulation.

5.0 INFORMAL USABILITY TESTING

Throughout the development of the LDUA simulator, volunteers (engineers, student interns, secretaries) participated in usability testing of the arm controller. These usability tests were informal in that, while written notes were taken, the sessions were not scripted or video taped. These sessions were invaluable, both in terms of debugging of the software, and developing the HMI.

5.1 LESSONS LEARNED

The following lessons were learned/modifications were made as a result of the informal usability testing.

- For joint space operation, the original HMI design specifications call for the operator to first select the joint she wishes to move and then to manipulate that joint. Each joint in turn must first be selected before it may then be moved. This mode of operation will be termed *single joint* mode. Single joint mode was found to be a usable mode for operating the LDUA.
- A limitation with single joint mode is that the process of deciding what joint to use and then selecting it with the mouse interrupts the concentration of the operator upon the task that she is performing. This led to the development of *multi-joint* control, where each joint is mapped to a different degree of freedom on the joysticks. Multi-joint mode does not require the user to first select the joint before moving it as in single-joint mode. The two joysticks together have six degrees of freedom so up to six joints can be mapped at a time. After testing

different configurations, the following mapping of joints to joysticks was judged best:

Joint	Joystick	Joystick Axis	Movement
Mast	right	ΔZ	up/down
Shoulder Yaw	left	ΔZ	thumb left/right
Shoulder Pitch	left	ΔY	forward/back
Upper Elbow	left	ΔX	left/right
Lower Elbow	right	ΔX	left/right
Wrist Pitch	right	ΔY	forward/back

The wrist yaw and wrist roll joints remain at this time unmapped, and can only be manipulated through single joint mode. Various strategies are being considered for accommodating these joints, including looking for 4-axis joysticks, or the addition of a third joystick with two axes.

- The proposed shoulder camera and overview camera's field of views are much too narrow. Further usability testing focused on determining the "ideal" (a realistic lens specification with a 4:1 zoom ratio) camera lenses.

- The 241-A-105 tank is complex environment, and there is a need in the simulation for a "training facility", a non-tank, non-threatening environment. Such a training facility was built for the formal usability testing. The advantages of the training facility are three: 1) It allows for straight forward, basic testing of the HMI 2) It provides an opportunity for operators to first become familiar with the LDUA in a 'non-threatening' environment, i.e. there would be no danger of colliding with obstacles allowing the operator to concentrate on learning how to manipulate the arm. 3) It provides a benchmark for non-optimal tank environment performance.

- Some sort of compass overlay is needed for in-tank operations, otherwise it is too difficult to determine the position and orientation of the arm relative to the tank. A compass feature (eight points of the compass were marked on the walls and floor of the tank) was included in the World Model that could be turned on or off.

- End effector orientation can be difficult for operators to determine. Therefore, an indicator was placed on the end effector labeling which side is up relative to the end effector camera view.

- Determining which joints are moving, and their joint limits can be difficult for operators. A color coding scheme was developed for the LDUA for joint space control where the color of a joint changed while it was moving.

- An exponential response was preferred from the joysticks rather than a linear response. This allowed access to both high and low speed operation, with good control at low speed, without having to "shift gears" with the mouse.

6.0 FORMAL USABILITY TESTING

Three tank farm operators participated in a total of 10 hours of formal usability testing. A written script was prepared and used as a guide to the test administrator to ensure that instructions to the operators were consistent and complete. This script had specific tasks for the operators to perform at all times. A copy of the script used can be found in appendix B. The usability sessions started with a introductory session in the training facility and progressed to tasks in the simulated tank. The sessions were video taped and included a post-session survey, question and answer debriefing. The survey is used as a means of extracting user comments on everything from very specific details of the system, to overall impressions. A copy of the survey can be found in appendix C.

6.1 LESSONS LEARNED

The findings from the formal usability studies are as follows:

- The lens specifications for the shoulder camera on the LDUA *should be changed* to allow for wider angle viewing. The current specifications are:

  Image Plane Size = 8.17 mm
  Focal Length = 22 to 90 mm
  Field of View = 21.0 to 5.2 degrees

  Instead, results from usability studies indicate that the shoulder lens should be:

  Image Plane Size = 8.17 mm
  Focal Length = 6 to 24 mm
  Field of View = 68.5 to 19.3 degrees

- The lens specifications for the overview camera on the LDUA *should be changed* to allow for wider angle viewing. The current specifications are:

  Image Plane Size = 10.991 mm
  Focal Length = 22 to 90 mm
  Field of View = 28.1 to 7.0 degrees

  Instead, results from usability studies indicate that the overview lens should be:

  Image Plane Size = 10.991 mm
  Focal Length = 4.7 to 18.8 mm
  Field of View = 98.9 to 32.6 degrees

- Operating the LDUA in joint mode (joint space, as opposed to cartesian space) is a very a very acceptable mode for controlling the arm. While it is recognized that there are more sophisticated modes for running the arm, joint mode is considered sufficient and usable for completion of proposed mission 1 in-tank tasks.

- Single joint control in joint mode is an acceptable and usable method of control, but not efficient.

- Multi-joint control in joint mode is a very acceptable and usable method of control. Multi-joint is preferred over single joint control, because less time is spent selecting the joint to move, and the operators could and did operate more than one joint simultaneously.

- Color coding of the joints in joint mode *greatly* assists the operator in running the robot. The color coding used consisted of:

  -Turning joints green whenever they are being moved.
  -Turning joints red whenever they reach a joint limit.
  -Turning joints white at 45 degree increments (+/- 0.5 degrees)

  In fact, reason to believe that the mental models operators develop to run the arm are entirely dependant upon the color coding of the arm. In other words, the usability of joint mode is greatly improved, and may in fact be dependant upon the color coding of the joints.

- Deadman switches on the joysticks were specifically requested by the tank farm operators. The current joystick triggers have functioned well as deadman switches throughout the usability testing.

- The simulator is an incredibly useful tool as a LDUA operator trainer. Just a short time on the simulator gives an excellent understanding of how the arm moves. Also, the operators requested more time on the simulation than the usability test needed - they wished to better understand the system and become more proficient strictly for their own purposes.

- The up/down grip motion on the transnational joystick is inadvertently pressed against repeatedly during arm operation. Strongly recommended that instead of the entire grip moving up and down, the third degree of freedom should be an up/down thumb lever.

- Labeling the joysticks according to their corresponding joints improves usability while operating in joint mode.

- All camera views in the simulation should be labeled with the camera identity. This may be more difficult with the video monitors in the actual LDUA System.

- Some sort of compass overlay is essential for determining position and orientation within a large tank. The current compass feature in the simulation works well.

- The method used in the simulation for using the mouse to control the values of a joint or camera received mixed reviews and is probably not acceptable. This method was a two step process where the operator first selected a joint by clicking on the appropriate button and holding the mouse down. At that point, the position of the cursor on the screen was used as a velocity input to the joint - the magnitude of the velocity was proportional to the distance of the cursor from a diagonal line bisecting the screen, and the direction of the velocity was related to whether the cursor was above or below the line. This approach was used as an expedient because IGRIP does not provide sliders or scroll bars.

7.0 FUTURE WORK

Current user testing has been limited to the arm controller operating in joint mode, and to a World Model of a 1 million gallon tank. The second round of usability testing is currently scheduled for early 1995. Future usability testing includes the following possibilities:

- Multi-joint mode with all 8 joints mapped to the joysticks. This would involve adding a third joystick, or perhaps instead using two 4 axis joysticks.
- Joint mode operation is a low level mode of control, which is the only mode tank farm operators have seen so far. Testing of cartesian motion, dependent upon the controller for a 7 and 8 joint arm to perform the inverse kinematic calculations, should also be conducted.
- Mission 2 and mission 3 of the LDUA call for more advanced automation for the LDUA. Usability testing could be used to determine which automated features would have the highest benefit to the operators.
- The current controls are not the actual control screens. As the real control screens are developed, they should be interfaced with the simulator and user tested.
- the LDUA is actually a two person operation. Safety procedures will require both the arm and the data acquisitions operators to be in the control trailer at all times. However, while the different titles may imply otherwise, the two positions are not mutually exclusive. Operating the arm and collecting data from the end effector are not independent events, and the exact relationship between the two operators is still not clear. While not a traditional use of usability testing, it should be possible devise usability studies to determine the best possible division of tasks between the two operators. This would involve expanding the simulator to include the data acquisitions workstation.
- There is current discussion about deploying the LDUA into places in addition to the single shell tanks, such as the 20 foot tanks and the annulus of double shell tanks. World Models of these environments should be constructed and deployment of the LDUA simulated.

8.0 CONCLUSIONS

The first stage of usability testing for the LDUA HMI has proven to be valuable and has resulted in several improvements being identified. Resources permitting, it should be continued.

Usability testing has also engaged the actual operators of the system and has given them a sense of ownership of the system even before its completion.

9.0 ACKNOWLEDGEMENTS

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APPENDIX A: TOP LEVEL TASK ANALYSIS

PHASED IMPLEMENTATION

The LDUA system is being implemented in stages. The first stage, called mission 1, is concerned with visual surveillance and inspection of underground storage tanks (USTs). Mission 1 activities include the LDUA hot demonstration and surveillance activities in other tanks covered under the Operational Readiness Review (ORR) for the hot demonstration. Presently, this ORR is expected to be limited to non watchlist tanks. The mission 1 control and data acquisition system will provide manual control of the mast and arm and will provide varying amounts of automation for operation of the End Effectors (EEs). Coordination between the arm operation and the EE operation will be the accomplished by cooperation and communications between the arm operator and the EE operator.

Mission 2 would involve operations that contact the surface of the waste or the tank, such as in-situ chemical analysis of the waste. The control and data acquisition system would need to be upgraded to handle such things as coupling of arm motion to proximity detectors on the End Effector. More task automation and increased integration would be necessary in order to automate the coordination between arm and End Effector operation could be provided at the supervisory level - how much and what kind are questions that the usability testing program might be expected to help answer.

The mission 3 would involve operations that penetrate the surface of the waste. The control and data acquisition system would need to be upgraded so that the arm would be able to exert controlled force in order to push End Effector probes down into the waste. Additional automation could also be provided at the supervisory level to help the operator with these tasks as well.

At present, only mission 1 has a firm budget, scope, and schedule, missions 2 and 3 remain in the planning phase.

TASK DESCRIPTION TABLE

The attached table contains brief, high-level descriptions of operator tasks. It is organized on two levels, first by the kind of operation (e.g. maneuvering in the vapor space), and second by End Effector. There are two columns, one for manual operations, and the other for automated operations. In general, the manual operations are planned for mission 1, and the automated operations are proposals for mission 2 or mission 3. However, there is a specific statement about each feature concerning its status.

Many of the terms used in the table are explained in the notes section following the table. The terms are referenced to the notes by superscript numbers.

Vapor Space - Operate the End Effector in the volume of the tank above the waste		
End Effector	Manual Operations[1]	Automated Operations[2]
Video and Photo Cameras	The arm operator would move the mast/arm at will to point the End Effector at the tank structures or waste surface. Both operators would study the video monitor for visible features of interest. The arm operator would then maneuver to bring specific feature into closer observation and the EE operator would initiate video/photo recording on demand. <Planned for Mission 1>	The system will automatically survey and record video/photo coverage of part or all of tank. The operator would specify which area of tank to cover, and possibly other parameters such as at what magnification and lighting intensity. The system would then calculate traversal path and increments over which to trigger the photo camera, and then execute the sequence. <Feasible for mission 2 >
Tank Mapping End Effector (TMEE)	The arm operator would position the mast/arm to point the TMEE at feature of the tank or waste, the EE operator would then take a scan, and obtain specific distance readings from scan. This process would be repeated as necessary <Originally planned for Mission 1 - postponed due to reduced funding>	The system would automatically build a 3D model of desired part of the tank internal space. This would require moving the End Effector to many different positions, capturing scans, and merging scans into a solid model (data fusion). <Feasible for mission 2 or 3 > Note: This capability requires that further development be undertaken in several areas, notably in understanding the problems in accuracy and registration with the instrument operating from the end of the arm (as opposed to anchored to rigid base at a known location), and also with data fusion software
Overview Video (Note: this is deployed down a separate 4" riser)	The EE operator will control the pan and tilt of the camera, and other parameters such as zoom, focus, and lighting, so that operation of the arm can be observed. Also, the Overview Video system could be used to visually inspect the tank structure and waste surface for significant features which could then be investigated by arm mounted EE. <Planned for Mission 1>	The system would control the pan and tilt of the camera in order to automatically follow the End Effector on the end of the arm (or some other part of the arm). Also, the system could cause the viewpoint of 3D World Model to automatically track that of the Overview Video camera. <Feasible for mission 2 >

Tank Contact - Operate End Effector in contact (proximity or touch) with tank structural features[4]		
End Effector	Manual Operations[1]	Automated Operations[2]
High Resolution Stereoscopic Video Camera	The arm operator would move the mast/arm at will so that the End Effector has close up view of tank structures. Both operators would study the video monitor for visible features of interest. The arm operator would then maneuver to bring specific feature into closer observation and the EE operator would initiate video recording on demand.. (Note: Since contact operations involve close proximity to tank surface, operators may need to monitor proximity sensors.) <Planned for Mission 1>	The system would automatically survey and record coverage of region of interest on surface. The operator would specify which area of tank or waste surface to cover, and possibly other parameters such as at what magnification and lighting intensity. The system would then calculate traversal path and then execute the sequence. <Feasible for mission 2>
Nondestructive Examination (NDE)	The arm operator would move the mast/arm to position the End Effector onto or near surface, perform. The EE operator would operate the End Effector, scanning for surface and sub-surface defects[3]. Operators may need to monitor stand-off proximity monitor during final placement. <Planned for Mission 1> Note: The INEL hot demo may be the best first use for this End Effector.	System would automatically survey and record coverage of region of interest on surface. The operator would specify which area of tank surface to cover. The system would then calculate the set of points on the surface at which the End Effector would need to be placed, and then go through the sequence of placing the End Effector, taking a reading, and moving to next position. Variant: System could move End Effector to a point on the surface adjoining the current position so that overlap with current spot is assured and optimized - system calculates placement and goes there. <Feasible for mission 2>

Waste Contact - Operate End Effector in contact (proximity or touching) with surface of waste[5]		
End Effector	Manual Operations[1]	Automated Operations[2]
Multi-Sensor End Effector (MiniLab)	The arm operator would move the mast/arm to position the End Effector near the waste. The EE operator would then take one or more readings. Since operations would involve close proximity to waste surface, operators may need to monitor proximity sensors. <Feasible, but not planned> Note: INEL is interested in this End Effector for their hot demo. Hanford might become interested in the gamma radiation measuring and vapor analysis capabilities of this End Effector.	System would automatically survey and record coverage of region of interest on surface. The operator would specify which area of surface to cover. The system would calculate traversal path and the specific points to take readings, and then do everything described in the manual case at each point. <Feasible for mission 2>

Depth Penetration - Operate (part of) End Effector below surface of waste[5]		
End Effector	Manual Operations[1]	Automated Operations[2]
RAMAN Spectroscopy	The arm operator would move the mast/arm to position the End Effector to the desired entry point above surface of waste, orient it the to desired angle of entry, and insert the probe into waste along angle of entry (probably a relative move in tool space) This operation might require the monitoring of proximity sensor readings, and reactive force at the TIP . The EE operator would obtain RAMAN readings at desired points during and after insertion. <Feasible for Mission 3> Note: Requires modification to Spar Subsystem Controller for force control>	Automatically survey and record coverage of region of interest of waste. The system would be required to calculate traversal path and the specific entry points, and then do everything described in the manual case. <Feasible for Mission 3> Note: This is a somewhat complicated operation and it is recommended that some further development work be done.
Waste Sampler	[TBD, but probably similar to above] <Feasible for Mission 3> Note: Requires modification to Spar Subsystem Controller for force control. INEL is interested in this End Effector for their hot demo.	[TBD]

Grasp/Move Objects in Tank		
End Effector	Manual Operations[1]	Automated Operations[2]
Gripper	The arm operator would move the mast/arm to position the End Effector over object, making fine motions to align the jaws with the object. The arm operator would then close the jaws, and move to new position. (the gripper End Effector will have its own video to allow accurate final alignment with object) This operation might require the monitoring of proximity sensor readings, and reactive force at the TIP. Note: a number of things identified in the LDUA Utilization Study could be covered - i.e. placement of sensor packages, servicing of retrieval arm, etc. <Feasible for mission 1, 2, or 3> Note: Requires sponsor to support development of suitable End Effector.	This would require the system to recognize an object in the tank and to determine its location and orientation, move to it, orient the gripper to best grasp it, and then actuate the gripper. It is not obvious how much of this task could or should be automated. Object recognition is in research and development stage. The use of proximity sensors to help guide the gripper placement is more understood, but would require some development. <Feasibility is unknown> Note: this is very advanced capability and would require further development. cost/benefit should be considered before that>
Sluicer	The arm operator would move the mast/arm to position the Sluicing End Effector and orient to the surface. The EE operator would turn the sluicing flow on and off and otherwise regulate it. This operation might require the monitoring of proximity sensor readings, and reactive force at the TIP. <Feasible for mission 3. It is also being proposed for ORNL and INEL hot demos> Note: This would require modifications to Spar Subsystem Controller to handle reactive forces from sluicer>	The system would automatically traverse and remove layer of waste. This would require the ability to for the system to use sensors on the End Effector to follow the contour of the waste surface at a preset standoff distance, and possibly to adjust traverse speed according to flow conditions of waste slurry outflow. <Feasibility is unknown> Note: a considerable amount of development would be required before this could be considered practical>

Operations in TRIC		
End Effector	Manual Operations[1]	Automated Operations[2]
Riser Alignment End Effector	Using video camera in the alignment End Effector, the arm operator will move the positioning table on the Mobile Deployment System (MDS) axis in small increments until images of bottom and top riser openings are concentric and centered on target in monitor (bore sighting). The EE operator would use the INEL-type laser gage[7] to confirm clearance with riser walls. This operation is expected to be performed from OCT at beginning of shift prior to riser entry. <Planned for Mission 1>	The system would automatically control the MDS to align the images of the top and bottom riser openings. It would then use the INEL-type[7] laser gage to confirm alignment. <Feasible, but not planned> Note: Modifications to the Spar control system (closed loop control of MDS) would be required. Development of image analysis software would be required. Development of the INEL-type laser gage[7] would be required.
End Effector Exchange System (EEES)	Manual operation of EEES would only occur under off-normal conditions, for example, to clear a jam in the mechanism. <planned for mission 1> Note: This is a local control capability for the Spar Subsystem Controller	Mount specified End Effector or dismount End Effector on TIP. This automated sequence is built into the Spar Subsystem Controller. <planned for mission 1>

World Model		
End Effector	Manual Operations[1]	Automated Operations[2]
n.a	A priori information (e.g. tank drawings will be used to construct a tank model as the basis of a World Model. This must be done by a designer /engineer /technician using the CAD feature of IGRIP. This should be a reasonably quick process of adaption for each new tank, once the first few tanks are in the system.	Other than the odd chance of taking advantage of some tanks having been recently re-drawn in AutoCAD, automated production of the basic tank model is not really applicable or feasible.
Topographical Mapping System (TMS) (Note: this is deployed down a separate 4" riser)	The surface contour of the waste will be added to the World Model from data obtained by the TMS. The baseline coordinate system of the TMS and the LDUA will be known to a reasonable accuracy, but the final registration of the TMS data with the tank structural model will be done by human eye and judgement. <Planned for Mission 1>	The system would automatically incorporate the TMS data into the World Model by means of data fusion software. <Feasibility unknown> Note: Commercial or production-grade data fusion software for the LDUA task does not appear to be available - an ORNL study in FY95 will study the possible solutions and make recommendations>
Tank Mapping End Effector (TMEE) (also discussed in the "Vapor Space" section above)	The TMEE can be used to get spot distances between the arm and specific features in the tank. This can allow the operator to move structural features (e.g. risers) of the tank model around that are not actually quite where the drawings showed them to be. <Planned for Mission 1>	The system would automatically incorporate the TMEE data into the World Model by means of data fusion software. This would require that the TMEE operation be automated as described in the "Vapor Space" section above. <Feasibility unknown> Note: Commercial or production-grade data fusion software for the LDUA task does not appear to be available >

NOTES:

1. Manual operations :

   a. Spar will provide 2 3-axis joysticks for teleoperation (one for translation, one for orientation).

   b. Operator can directly teleoperate the mast/arm by using joysticks and visual feedback.

   c. Operator can indirectly teleoperate the mast/arm by using joysticks and the simulation mode to preview motion in the IGRIP display and can construct an autosequence during this teleoperation. Collision checking can be enabled during indirect teleoperation, but may cause the simulation to bog down.

   d. A good question is whether it will be desirable or possible to provide auxiliary controls on the joysticks, such as buttons, that may be assigned to control End Effectors (e.g. camera tilt, lighting and zoom; gripper open/close; photo camera shutter; control of video on/off) [This may be a Mission 2 capability, at best]

2. Automated Operations:

   a. For mission 1, the operator can construct an autosequence by typing coordinates and angle of orientation for each goal point in the sequence at the keyboard. An autosequence can be loaded from or saved to a file. Autosequence files could be constructed by an off-line path planner.

   b. The option for semi-automatic operation (i.e. single stepping through sequence) is to be provided wherever possible.

   c. Advanced control system features would allow autosequences to be generated automatically from task-level "scripts" using advance automatic path planners. These scripts could also control the operation of End Effectors.

3. It is not clear that the EE operator alone can perform operation of the Non-Destructive Examination (NDE) end effector. Normally, NDE requires very specialized training for the users, and an extensive program to be set up to qualify and certify the equipment and operators.

4. Structural features are parts of the tank (eg. risers, wall, saltwells, dome, floor) and have generally straightforward regular geometry and shape, size, and location are considered reasonably predictable from a priori information (e.g. tank drawings), and are thus practical to model by hand.

5. It is assumed that the waste surface may be irregular and not predictable from a priori information, and therefore not practical to model by hand.

6. Spar is designing their control system to provide two levels of operator

access privilege: "supervisor" and "operator". "Operator" has access to enough of the system to operate the system. The "supervisor" can do that, plus is allowed to change certain system parameters.

7. The "INEL-type" laser gage is a device for checking the diameter of a riser. It uses a beam of laser light on a rotating base operated such that the laser beam sweeps out a perfect cylinder within the riser. The laser beam can be moved so that the cylinder diameter can be larger or smaller than the riser inside diameter. If the laser gage can sweep out a cylinder of a diameter larger than the LDUA without the beam touching the riser wall, the alignment of the LDUA to the riser will be acceptable. Note: a device using this basic principal has been used at INEL.

APPENDIX B: SCRIPT FOR FORMAL USABILITY TESTING

1. Introduction (Greetings, introductions, show operators where to sit) :

Thank you for coming in today. Today's session is part of a series of usability studies whose purpose is to help us design and evaluate both the control/display interfaces for the Light Duty Utility Arm, and the operator tasks involved in examining a storage tank.

Everything we are evaluating today is with respect to the usability of the interface. Our purpose is to first uncover what problems may exist in the system, and then to find possible solutions. During this session you will asked to use the system for a variety of tasks. If difficulties or problems arise, or things are not happening *the way you would expect*, we want to know. The interface's job is to make your job easier, and if it is not allowing you to do something, then it is a problem with the interface and *not* a reflection upon you.

Towards this end, I'm going to ask you to use a "thinking out loud protocol" throughout the test session. This means I want you to think out loud, actually talk out loud, saying what it is you are trying to do and what you expect to happen. Feel free to give additional comments at any time during the session, for your comments and insights are the true purpose of this session.

An ideal interface is one that is transparent, one that is not noticeable to the user. Aspects of the interface that receive no comments are therefore assumed to be working and contributing to the goal of a "good interface". Again, we are counting upon your inputs to improve/test the interface and features which do not get commented upon will probably remain the same in the real system.

As you can see, we are video taping this session, but all we are recording are the control devices and the monitor display.

Today's session has three main parts: a LDUA training session set up in a simulated training facility designed to allow you to gain a familiarity with the arm and interface, and the second part is a simulation of actual in-tank operations where you will be asked to carry out tasks which are modeled on proposed LDUA deployment tasks. After the training and the in-tank sessions there will be a question and answer survey session covering various aspects of the system.

If at any time you would like take a break or get something to eat or anything, there should be no problem, just let me know. So, before we begin the training session, any questions?

2. Training Session (start-up igrip training program)

First I'd like to explain that a lot of what are going to see today are mock-ups of the proposed LDUA system. This is only a simulation, the real system will be very different than what we have here. For example the camera views provided by the end effector, shoulder, and overview cameras are being simulated today using the Silicon Graphics machine, while in the real system those views would be displayed by three separate television monitors. Also, in the real system most of the control rafts you will see on the SGI will actually be on the Sun workstation monitor, leaving this screen free for viewing the World Model. So while the actual system will be very different, we believe that this current set-up gives an accurate sense of what operating the LDUA will feel like. As we go along and they become relevant, I'll point out other differences between this set-up and the real system.

We'll start with familiarizing you with the camera views and their pan, tilt, zoom, and move ranges.

2b. Camera Views

What you are seeing now on the screen is a view of the LDUA in a what we are calling a "training facility". This is the arm, the end effector camera, the shoulder camera, the overview camera is over here, and this is a section of tank wall with a few points of interest on it. There are also a few risers sticking through the ceiling and there is an air circulator tower on the ground.

This view of the world, what we are seeing now, is not through any of the camera views and is what we are calling our "simulated" camera view. This view exists only in our simulation.

We're going to now flip the view to see the world through the other cameras. Using the mouse, move up to the "Video Switch" button and click on it. This is the raft which controls which views are shown and their arrangement. Currently the arrangement is "Single View", so that means 1 view, what ever is shown in view 1, gets shown. Notice that View 1 says "Simulation", which is what is being shown on the screen.

-Change View 1 to read "End Effector" then using the mouse click on "Done".

-Change View 1 to read "Overview Camera" then click on "Done".

-Change View 1 to read "Shoulder Camera".

-Change View 1 back to the "Simulation" view.

You also have the option of setting up multiple views at a time. Once again, using the mouse, move up to the "Video Switch" button and click on it. Move the pointer to the top line which says "Arrangement" and click on it, then say "Done". Identify which views are showing in each screen. Toggle through the rest of the multiviews, identifying the different cameras.

Depending on the camera, different cameras may allow for control of their position, pan, tilt, or zoom functions. For example, the end effector camera allows for control of its zoom.

Make sure the video switch arrangement is toggled to "Single View" and set view 1 to "End Effector". Select the "Pan/Tilt" button to bring up the camera functions. To zoom the camera view in or out, press the "Zoom In/Out" and hold the mouse button down. Now by moving the mouse either down or to the left will zoom out the view, while moving the mouse up or to the right zooms in the view. Zoom the end effector camera full out, then full in, then return to a comfortable viewing position.

Toggle the video switch, set view 1 to shoulder camera. Besides zoom, the shoulder camera also has additional control of pan and tilt functions. Pan the shoulder camera full right, full left, then return to a comfortable viewing position. The shoulder camera has a pan range of +/- 70 degrees. Tilt the shoulder full up, full down, then return to a comfortable viewing position. The tilt range is from straight horizontal to down 40 degrees. Zoom the shoulder camera full out, full in, then return to a comfortable viewing position.

Toggle the video switch, set view 1 to overview camera. The overview camera also allows for control of its position up and down in the tank. Move the camera down, then up some, then return to a comfortable viewing position. Go through the complete pan, tilt, and zoom ranges and choose a comfortable viewing position.

Toggle the video switch, set view 1 to simulation. While no camera will actually exist in the tank to give this view, the simulated view has been set up as if it is a camera view. The simulated view, which is also known as the World Model, will based off tank design schematics and merged with laser range data. Most likely, points of interest would not show up in the World Model view, and its main purpose would be for determining the position of the arm relative to the tank. The simulation camera control also allows for position control to the left and right of the view and moving in and out of the view.

2c. Joint Manipulations

Before we start into joint manipulations on the arm, set up the arrangement and the individual views to allow you optimal viewing of the arm and tank. From here on, you are expected on your own to identify when it is necessary to adjust views or the arrangement. Modify the views as necessary, and whenever necessary, before or during individual tasks within the tank.

The mode of LDUA operation we are testing today is known as Joint Space control. It is recognized that joint space control is not an optimal control method. At this time it is believed that joint space control on the real system would rarely get used, but it is a possible control option. Joint space control is a low level type of control that would possibly be used in arm training (it best demonstrates the limits and capabilities of the arm), times where specific configurations are required but the inverse kinematics are too limiting (inverse kinematics pays no attention to obstacle avoidance, therefore joints may have be taken over manually), and arm failure recovery scenarios. In other words, it is a control mode that an operator would have be familiar with.

Including the mast, the LDUA has eight degrees of freedom, and six of them are mapped to joysticks. Each joystick is a three degree of freedom controller, and the other two unmapped joints must be controlled by mouse.

Let's run through the mapped joints first. Toggle the "LDUA" switch, then select the button labeled "Joysticks". The joysticks are now enabled. The raft that has appeared is a display of the individual joint values. Since that raft isn't needed for now, we can remove it by right clicking on the upper left hand corner of the raft.

All the joints are rate controlled, displacement of the joystick moves the joint slowly. Displacement of the of the joystick a greater amount moves the joint at a faster rate. The color green is used to indicate a moving joint. The color red is used to indicate a joint that has reached its joint limit. The color white is used to indicate that a joint is at 45 degree increment, -45 , 0, 45, 90...

The Mast is controlled by moving the right joystick up and down. Remembering that the deadman switches must be switched on in order to move a joint, deploy the LDUA downward as far as possible. Elevate the mast all the way up, and then deploy the mast to about its starting position.

The Shoulder Yaw joint is controlled by the thumb lever on the left joystick. Manipulate the Shoulder Yaw through its full range of motion, rotate the joint 180 degrees in one direction, then 360 in the other direction, then return to the home position.

The Shoulder Pitch joint is controlled by the forward/back motion on the left joystick. Manipulate the Shoulder Pitch through its full range of motion, rotate the joint up 105 degrees then return to home position.

The Upper Elbow joint is controlled by the left/right motion on the left joystick. Manipulate the Upper Elbow Yaw through its full range of motion, rotate the joint first 100 degrees in one direction, then move 200 degrees in the reverse direction, then return to the home position.

The Upper Elbow joint is controlled by the left/right motion on the right joystick. Manipulate the Lower Elbow Yaw joint through its full range of motion, rotate the joint 100 degrees in one direction, then move 200 degrees in the reverse direction, then return to the home position.

The Wrist Pitch joint is controlled by the left/right motion on the right joystick. Manipulate the Wrist Pitch through its full range of motion, rotate the joint 100 degrees in one direction, then 200 degrees in the reverse direction, then return to the home position.

Joints can also be manipulated one at a time using the mouse. Toggle on the "Joint" button. Select the Mast and deploy the mast all the way down. Bring the mast all the way up, then return to a deployment position. Go through the other joints running through their complete range.

Notice that control of the wrist pitch and wrist roll joints are currently only possible using the mouse.

Toggle the compass switch.

2d. Tasks

Use the end effector camera to get the best view of the crack.

Examine the blue spot on the wall.

Examine the square in the middle.

Scan the left surface of the wall covering the entire area containing the read leak.

3. Tank Session

This part of usability study is a simulation of an actually deployment inside a real tank. Collisions are a possibility and under no conditions is it permissible to collide the arm. IGRIP will provide you with a one foot proximity warning before a collision.

Provide a close examination of the crack on the east side of the tank.

Provide a close examination of the hole in the south side of the tank.

Provide a close examination of the underside of the center 42 inch riser.

Provide a scan of all leaks on the SW side of the tank.

Provide a scan of the entire NE to NW part of the tank, including the ceiling surfaces.

[Demonstrate the auto sequences, deploy, retract, scan.]

APPENDIX C: POST-TEST SURVEY

Cameras

1. The zoom range on the shoulder camera was

Excellent				Not Acceptable
1	2	3	4	5

Comments:

2. For operating the LDUA the shoulder camera was

Very Useful				Not Useful
1	2	3	4	5

Comments:

3. The zoom range on the end effector camera was

Excellent				Not Acceptable
1	2	3	4	5

Comments:

4. For operating the LDUA the end effector camera was

Very Useful				Not Useful
1	2	3	4	5

Comments:

5. The zoom range on the overview camera was

Excellent				Not Acceptable
1	2	3	4	5

Comments:

6. For operating the LDUA the overview camera was

Very Useful				Not Useful
1	2	3	4	5

Comments:

7. For operating the LDUA the simulation view was

Very Useful				Not Useful
1	2	3	4	5

Comments:

8. Using the mouse to control pan/tilt/zoom/move functions on the cameras was

Very Easy				Very Difficult
1	2	3	4	5

Comments:

9. Using the cameras to determine the position of the LDUA inside the tank was

Very Easy				Very Difficult
1	2	3	4	5

Comments:

Joint Coloring

10. The coloring of the joints green as they were moved was

Very Helpful				Not Helpful
1	2	3	4	5

Comments:

11. The coloring of the joints red as they reached their joint limits was

Very Helpful				Not Helpful
1	2	3	4	5

Comments:

12. The coloring of the joints white at 45 degree increments was

Very Helpful				Not Helpful
1	2	3	4	5

Comments:

Joystick Control in Joint Mode

13. The deadman switches on the joysticks was

Very Useful				Not Useful
1	2	3	4	5

Comments:

14. Controlling the mast using the up/down motion on the right joystick was

Very Easy				Very Difficult
1	2	3	4	5

Comments:

15. Controlling the shoulder yaw using the thumb lever on the left joystick was

Very Easy				Very Difficult
1	2	3	4	5

Comments:

16. Controlling the shoulder pitch using the forward/back motion on the left joystick was

Very Easy				Very Difficult
1	2	3	4	5

Comments:

17. Controlling the upper elbow using the left/right motion on the left

joystick was
Very Easy Very Difficult
1 2 3 4 5
Comments:

18. Controlling the lower elbow using the left/right motion on the right joystick was
Very Easy Very Difficult
1 2 3 4 5
Comments:

19. Controlling the wrist pitch using the up/down motion on the right joystick was
Very Easy Very Difficult
1 2 3 4 5
Comments:

20. Using joysticks to control individual joints on the LDUA was
Very Easy Very Difficult
1 2 3 4 5
Comments:

21. Using the mouse to control individual joints on the LDUA was
Very Easy Very Difficult
1 2 3 4 5
Comments:

22. Operating the LDUA in joint mode was
Very Easy Very Difficult
1 2 3 4 5
Comments:

<u>Other</u>

23. The compass function was
Very Useful Not Useful
1 2 3 4 5
Comments:

24. What kind of automation features would come in handy?
Comments:

25. In general, operating the LDUA is
Very Easy Very Difficult
1 2 3 4 5
Comments: