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CONSIDERATIONS FOR HUMAN-MACHINE INTERFACES IN TELE-OPERATIONS

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ABSTRACT

Numerous factors impact on the efficiency of tele-operative manipulative work. Generally, these are related to the physical environment of the tele-operator and how well he interfaces with robotic control consoles. The capabilities of the operator can be influenced by considerations such as temperature, eye strain, body fatigue, and boredom created by repetitive work tasks. In addition, the successful combination of man and machine will, in part, be determined by the configuration of the visual and physical interfaces available to the tele-operator. The design and operation of system components such as full-scale and "mini"-master manipulator controllers, servo joysticks, and video monitors will all have a direct impact on operational efficiency. As a result, the local environment and interaction of the operator with the robotic control console have a substantial effect on mission productivity.

INTRODUCTION

The telerobotics field is wide ranging and encompasses work in several disciplines. Some of the typical uses of telerobotics systems today are in underwater inspection and work operations, inspections of nuclear power plants, the operation of remotely piloted vehicles (airborne RPVs), and the disposal of unexploded ordnance. But of all the contemporary applications of telerobotics, the subsea field is certainly one of the most diverse uses of telerobotics technology. As a result, the subsea field offers one of the most varied databases of operational experience for study, regarding all aspects of operator interfacing with robotic hardware.

Underwater telerobots must be designed specifically with the environment in mind. Both in space and underwater, the challenges to the designer are significant if they are to provide equipment that can accomplish the desired remote task on a cost effective basis. It is also not surprising that the existing subsea operator interfaces look very similar to their proposed space counterparts, given the similarities of the design drivers for both environments.

The designer of telerobotics workstation interfaces for the space environment faces much the same problems as anyone developing equipment for the underwater environment. The consoles must be compact, and capable of supporting remote work on a 24 hour basis. In addition, the console interfaces must be compatible with the operator, so they can work for extended periods with minimal fatigue. Also, consoles designed for both environments must offer the capability of positioning the robotic work system and operating its manipulators. Consequently, an examination of the subsea robotic field can help pinpoint areas of concern with regard to operational environments and the interfaces between the teleoperator and the work system.

The human factors related to remote work tasks must also be considered. Robotic work systems are hardware designed to be operated by humans. As a rule, humans work more efficiently if the local environment is comfortable and free of distractions. The same will be true of space based teleoperations. Therefore, the human factors and lessons learned by the design and operation of subsea telerobotic control consoles are directly applicable to space robotic operations. Most subsea robotics workstations incorporate many of the basic functions required of both on-orbit and ground-based space robotic control stations.

PHYSICAL AND ENVIRONMENTAL FATIGUE FACTORS

The efficiency of the human-machine interface is determined by two factors: the operator's local environment and the compatibility of the workstation to operator interface.

The Teleoperator Environment

The teleoperator is affected by their local environment as is any individual attempting a task requiring high degrees of concentration. Factors such as the ambient temperature, noise levels, seating orientation, and the mental state of the individual will take on a more important role than in less demanding situations. In addition, the length of time that the operator is required to concentrate his attention on remote tasks will greatly influence the onset and degree of operator fatigue.

There are several ways a teleoperator is affected by the local environment. Some of these concerns relate to the actual physical environment, while others have to do with the nature of the remote work being attempted. Operational stress is generally created in situations where the work task is extremely difficult, whether it be because the robotic system is being operated outside of its capabilities or has experienced some type of failure. Typically, even if manipulators or related equipment are only partially operational, the job will continue because of cost or criticality concerns. This type of situation is very trying for the operator because they are attempting a task outside of the nominal method of operation. However even with a fully operational system, complex work tasks can take their toll on the operator due to the required amount of concentration. Consequently, the onset and level of operator fatigue is directly related to task complexity. Manipulator operators can "burn out" after only 30 minutes during difficult operations, whereas in other cases with less demanding tasks, they can function productively for several hours.

Eye strain is another problem with extended teleoperations. Usually, the degree to which this is a factor is related to the length of operations, and the size and quality of the video image. Fuzzy or partially out of focus pictures can be irritating to look at for any length of time. Also, the speed with which the camera focus motors operate can contribute to this problem by making it difficult for the operator to get a clear picture on the video monitor. In this type of situation, considerable time is wasted as the camera lens continually runs past the optimum focus point by either being too near or too far. Cameras fitted with zoom lenses are notorious for this focusing problem.

As with any work environment, the ambient temperature must be comfortable and within the proper range of humidity. This concern is not only for comfort because robotic system microprocessors (as with most electronic equipment), only operate within definite temperature ranges. Related equipment such as high voltage transformers can dissipate tremendous amounts of heat, sometimes in an area located near the operator. These factors must be taken into account when specifying environmental control units and ventilation requirements for the teleoperations area.

The lighting conditions in the operations area is also a concern. Improperly placed or excessively intense lighting can cause glare on the video monitors making them difficult to see. All too often, personnel not directly connected with the job can frustrate and distract the operator by switching on nearby lights at the worst time. For example, the writer was trying to follow a lift line with a Remotely Operated Vehicle (ROV), during a deepwater operation under low visibility conditions. An individual opened the door to the control van (where the workstation was located), spilling bright ambient light onto the pilot's video monitor. The teleoperator immediately lost sight of the line and much time was wasted surfacing the vehicle and starting all over again.

In addition, excessive noise affects operator productivity. Occasionally, minimal consideration is given to the type of ancillary equipment operating near the control console. A high ambient noise environment enhances fatigue and also places unreasonable demands on the communications system.

Physical Factors

The physical interfaces between the operator and console also influence the practicality of doing remote work. All too often, the designers of robotic work consoles will not consider the physical movements required by the teleoperator to control remote vehicles and manipulators. The operations console must be looked at as the physical link between the operator and the robotic system; i.e., the path through which all of the operator's senses must receive visual and physical feedback from the robotic system, and the point of physical contact by which they direct the movement of the remote work system. This link, if flawed in any way, will degrade the ability of the teleoperator to communicate with the robotic system.

Body, joint, and hand fatigue is caused in several ways. First of all, any extended operations with large scale master arms (over 45 minutes), can result in arm fatigue. During the use of a master controller, the operator's arm muscles are constantly in contraction and extension as they attempt to position the slave arm. This, in itself, is not a serious problem. However, the level of concentration required during the task is passed down to the operator's arm, inducing a higher level of muscle tenseness than would normally be present. As indicated above, this is greatly influenced by the amount of visual concentration required to do the task. Generally, the problem manifests itself in the form of a very tight grip on the hand grip of the master arm. Like general operator fatigue, arm fatigue is directly driven by the difficulty of the remote task. Extended operations with miniature joystick controllers is also a problem. Hand fatigue is quite common during long term use of small proportional controllers (similar to the ones used in "Pong" games).

Body fatigue is created by the operator's seating position at the control console. Unfortunately, little thought is normally put into the design of operator's seating configuration and the amount of leg room available. Regardless of the type of restraint in use, for the operator to concentrate their attention on the job at hand, they must be comfortable and have room to stretch. However, extended zero-G operations will be a new application for teleoperator seating/restraint concepts.

Finally, long term repetitive teleoperations work, as a rule, can be somewhat boring. Once the initial fascination of the operation wears off, operator boredom will normally speed up the onset of fatigue, with the result that teleoperators can literally fall asleep at the console. This is particularly true during jobs where the work involves primarily supervision and little operator interaction with the equipment. The only way to combat the problem is to rotate operators on a frequent basis and vary their job requirements.

HUMAN-MACHINE INTERFACES

General Console Layouts

Telerobotic workstations come in a variety of configurations, but they all have a common purpose: to act as a two way conduit of operator inputs and robotic system feedback. Generally, the typical teleoperations console can come in two designs: a small portable workstation that is installed and used as needed, or a dedicated console that is permanently mounted in a specific operations area.

Portable Consoles

Portable consoles have been in use the subsea telerobotics field for over a decade and can range from small suitcase sized units to ones that are hand-held. The hand-held consoles normally encompass the basic system functions and are integrated with a separate video display. The larger portable consoles are similar, but usually contain the surface or upside system electronics. The primary problem with these types of consoles is that they must be set up before use and are very prone to damage if they are accidentally bumped in the process. Most of the internal electronics associated with these units are delicate and not capable of withstanding significant abuse. In addition, the time needed to prepare the robotic system for operation can consume valuable operations time. The other problem is that because of the console or controller's small size, some compromises are usually made with regard to the configuration of the robotic system functions. In other words, the quality of the operator interfaces can be degraded because of space or size limitations.

Dedicated Consoles

Dedicated consoles offer more flexibility, from the operational standpoint, because they have more console surface area onto which to mount the system functions; i.e., they can be optimized for the most compatible operator interface. The dedicated console will also make it possible to install "operator friendly" components such as larger video monitors (some dedicated to a single camera), larger sized hand controllers, and system diagnostics. In addition, since the consoles are permanently mounted in a specific location, they are not subject to any physical abuse, and enable the creation of a single-purpose area for teleoperations. However, the down side is that dedicated consoles require more IVA volume for installation and sometimes eliminate the possibility of using the area for other purposes.

Hand Controllers and Master Arms

Hand controllers are a direct physical interface point between the teleoperator and the workstation. Consequently, their design can have a significant impact on the overall compatibility of the control console. Large scale master controllers, as indicated earlier in this paper, contribute to operator arm fatigue during extended use. However, that is only one potential problem. While the large scale master does offer intuitive control and force reflective capabilities, they do require a large IVA work envelope for use. This can drive the interior design of the operations area in an undesirable way, in that it increases the free-volume requirements for the location. In addition, the masters can at times be delicate contraptions that are easily damaged, and require somewhat elaborate stowage schemes to keep them out of the operator's way when they are not in use. While master arm indexing can reduce the volume required for use, this feature can detract from the primary advantage to using a large scale master in the first place; that the master kinematically represents the current position of the slave manipulator.

"Mini" masters represent a departure from their large scale counterparts in that they offer a kinematic replication of the scale arm, albeit on a smaller scale. Like the larger masters, they are subject to breakage and stowage problems. Unfortunately, there are not yet any commercially available "mini" masters with force reflection.

"Bang-bang" rate controllers are limited in capability in that they can only be used with rate manipulators. However they are generally simple in construction, highly reliable and offer an extremely small IVA work envelope. Another advantage to rate controllers is that they give the operator the opportunity to do manipulative work on a part-task basis because the arm automatically freezes when the operator removes his hands from the controller. While the same could be said of large scale and "mini"master controllers, the rate controller offers this capability as an inherent function of its design.

Proportional joysticks can be used for end point control with resolved rate type manipulators. Depending upon their physical size and design, they are comfortable or fatiguing to use. Typically, these types of hand controllers are integrated with controls for ancillary functions such as camera pan, tilt, focus, and zoom. While this is a desirable feature, it can sometimes get out of hand. There are only so many functions an operator can memorize on one control stick, and while it is highly desirable to incorporate multiple functions on one controller, there should not be so many that the operator has trouble memorizing the individual functions, or can accidentally actuate a function during normal operations.

SPECIFIC RECOMMENDATIONS AND CONCLUSIONS

Environmental

There are several conclusions that can be derived from the information presented in this paper, but one is obvious: the local environment of the teleoperator has a significant and measurable effect on the efficiency of doing remote work tasks. As a result, steps must be taken to guarantee that the environment of the operations location is favorable to practical work.

Some of the recommendations that will aid in the above goal are as follows: While it seems like a logical concern, the temperature of the telerobotics operations area is a factor that is often overlooked. The operations location must be comfortable to the teleoperators or they will have difficulty concentrating on the job at hand. The amount of heat generated by control consoles themselves is sometimes minor, but related support equipment can radiate large amounts of energy (this is of particular concern if ventilation within the operations area is lacking). The designer must consider these facts when specifying the requirements for environmental control equipment. In addition, the expected environment of the exterior of the control area, must be considered with respect to any external influences (direct sunlight, radiation, etc.).

High noise levels in the operations area can also cause problems, especially with regard to communications. A high ambient noise level will drive headset needs in an undesirable manner. Communications headsets should be able to be selected on the basis of their comfort and clarity, not sound isolation properties. Finally, as with temperature, excessive sound levels will increase the onset of operator fatigue. Any equipment expected to generate high noise levels should be isolated from the teleoperations area, if possible.

Body and hand fatigue will become a significant negative influence during any extended teleoperations. But how much of a factor it becomes will be determined in part by the design of IVA restraints and hand interfaces. As a result, there are specific areas of concern that can be dealt with to reduce fatigue problems. First of all, hand controllers should incorporate some form of hand or forearm rest to help relieve operator muscle tension. For the proportional joystick, possibly some type of padded area (similar to an arm rest on a chair) that the operator can place his arm against would be beneficial. In the microgravity environment, it may be necessary to supply a flexible restraint to hold the arm against the rest during operations. Obviously, a force reflective system will demand some form of restraint if the teleoperator is to have any hope of "feeling" mechanical feedback generated by the master arm.

Operator restraints should be highly adjustable, with regard to their orientation with the control console, and general configuration. The restraint should be flexible enough to fit a wide range of operations personnel (this is especially true during any operations involving force reflection, since the operator will measure the physical feedback while using the restraint as a stop). In addition, there should be sufficient IVA free volume surrounding the operator restraint to allow for body flexing (especially the legs) during extended IVA operations.

Operational stress will be a driving force behind the onset of operator fatigue during teleoperations. This stress can manifest itself in several ways but primarily, it will be related to task difficulty. Highly complex manipulative operations, especially those that involve work on the borderline of system capabilities, will be extremely fatiguing to operations personnel. For example, if a manipulator has an end point positioning accuracy of plus or minus 1", and the arm is being used to assemble components that have .90" clearance around them, then clearly, it is going to be a difficult time for the arm operator (especially if the components have been designed without alignment guides). Consequently, in these types of situations the operators should be changed out on a frequent basis.

The number of degrees of freedom the operator is required to operate can also influence operational stress levels. Typically, pilots of subsea robotics systems have been able to do simultaneous operations such as combined vehicle and manipulator operations at mid-water. However, such accomplishments were normally under good conditions using only 3 - 4 DOF arms. This maximum DOF issue is one that requires further study.

Job stress is also related to how well the robotic system is operating. Equipment that experiences excessive down time will frustrate teleoperations personnel because they will spend more time repairing the equipment than operating it.

The quality and type of video monitors impact productivity by contributing to operator eye strain. Individuals doing teleoperations do not just "look" at video monitors, but must examine and understand the visual information on the screen. Trying to do this with a degraded video image is difficult, at best. Some basic suggestions are that video monitors used for teleoperations should be at least 9" in size, and incorporate standard controls for brightness, contrast, and sharpness. In addition, the IVA work environment should offer indirect lighting of variable intensity. The distance from the video displays to the operator's eyes, as a general guideline, should be no less than about 3/4 arm length.

Physical Interfaces

Hand Controllers

The type of manipulative operation and design of the manipulator system should be the determining factors with regard to the configuration of arm controllers. While large scale master arm controllers can be very beneficial to teleoperations, they will cause arm fatigue if used for extended periods. Steps should be taken to ensure the availability of sufficient operations personnel for an acceptable rotation schedule during extended or complex manipulative work tasks. In addition, any full-scale masters installed in a robotic workstation should be capable of stowage during periods of non-use.

Proportional hand controllers should be sized in relation to expected task duration. Generally, if sufficient IVA console space is available, medium sized joysticks (that can be grasped by the entire hand), should be employed.

The designer should strive to make the hand controllers reflect the physical configuration of the manipulator system. In other words, the arm controllers should be referenced to the video monitor screen as a representation of how the subsystems are physically related at the worksite. The most important aspect is the video camera to end effector relationship. If the robotic system is configured with the video camera in the middle of two manipulators, then the two arm controllers at the workstation should be mounted on either side of the video monitor. The work station should represent the remote work system as much as is practical.

Standardization of teleoperator interfaces will aid operational efficiency by reducing learning requirements between different robotic systems. There are several ways that standardization can be applied to physical interfaces, but the most obvious solution, such as using identical controllers for several applications, is not necessarily the best; operator interfaces do not have to look alike to be standardized!

There are a multitude of telerobotic vehicles in use today in the subsea field, and outside of the individual manufacturers, there is little or no standardization. But what has been learned in the past decade of teleoperations is that standardization is more related to method of operation than appearance.

Some underwater remote vehicles are controlled by two joysticks while others can be driven with one. It all depends upon how the control subsystems are configured and the preferences of the manufacturer (some seem to prefer a one over a two stick arrangement). Field personnel who take over control of a vehicle with no prior experience on a particular system can usually learn the functions fairly quickly, especially if the operator is highly experienced. However, standardization of the operator interfaces would certainly reduce the amount of time it takes to learn a particular robotic system.

Robotic system controls should be standardized with respect to function and mode of operation. The key is to guarantee that identical physical movements are required of the operator to achieve a particular result. A standard typewriter is an excellent analogy. There are many varieties of typewriters, but in most designs, the keys (the separate letters, that is), are always in the same location. The typist can then learn one interface pattern, then have the ability to use all typewriters. The reason this is so important is that the teleoperator references all of their resultant actions (the physical movements they see on the video monitor) to specific movements at the workstation. The operator knows that if he moves a control in a certain direction, he will see a corresponding result on the video screen. This results in a "learned relationship" between action and reaction. This relationship is what is learned by the operator, not the shape, size, or color of the hand controller. As a result, systems that operate outside of this database of information have to be relearned all over again so the operator can develop a new action/reaction relationship. This process wastes time. Hence, the relative dynamic relationship between the operator and the controller is what should be standardized, not the physical design of the controller.

Control Consoles

Telerobotic workstations should be configured to act as the operator's reference point to the robotic system. First of all, if possible, there should be a dedicated video monitor for each camera. This will enable the teleoperator to instantly view the entire visual range surrounding the telerobot, without confusion as to what camera they are viewing. Of course, given the space limitations on-orbit, this may be impractical. A compromise would be to use video multiplexing so that the teleoperator can examine multiple video images on one video monitor. The goal should be to make sure the teleoperator knows which video image is being generated by what camera.

The mechanical orientation of manipulator controls should mimic the configuration of the telerobot as much as is feasible. For example, if the robotic system has two arms, then there should be two separate controllers instead of one controller with a selection switch.

Camera pan and tilt controls should also follow the same practice; i.e., there should be a separate controller for each camera. Ideally, pan and tilt controls should be incorporated into hand controllers so the teleoperator can operate the manipulator and camera controls without diverting their attention from the video monitor.

System functions should be unique and configured based upon their function. For example, the switches used to turn lights off and on should be of a different design than the ones that control system power. Ideally, the console should not need labels on all of the controls for the operator to know their functions. Overall, a customized function layout will reduce errors and enhance compatibility. The console should be ergonomic so that the operator can easily reach all of the system's functions without constant body movements. This feature will reduce body fatigue.

In general, the concept behind a telerobotic console should be to design for functionality, compatibility, and practicality. The foremost thought that should be behind the design of the console is that the workstation is the teleoperator's hands and eyes at the worksite.

Portable workstations that have to be set up or installed before use should be avoided, if it is at all possible. The types of compromises made in portable designs are sufficient to render them undesirable for extended teleoperations use. A far better arrangement is the design of a workstation permanently installed into a "teleoperations work area". This will enable the teleoperator to do the job at hand in the most compatible environment possible. However, in situations where it is absolutely impossible to create a dedicated area, such as in the Orbiter's aft flight deck, then any portable workstations should be highly adjustable, with regard to the installation point and mounting angle, so the teleoperator can customize the operator to workstation interface.