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"DUAL USE DISPLAY SYSTEMS FOR TELEROBOTICS"

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Abstract

This paper describes a telerobotics display system, the Multi-mode Manipulator Display System (MMDS), that has applications for a variety of remotely controlled tasks. Designed primarily to assist astronauts with the control of space robotics systems, the MMDS has applications for ground control of space robotics as well as for toxic waste cleanup, undersea, remotely operated vehicles, and other environments which require remote operations. The MMDS has three modes: 1) Manipulator Position Display (MPD) mode, 2) Joint Angle Display (JAD) mode, and 3) Sensory Substitution (SS) mode. These three modes are discussed in the paper.

1. Introduction

Manual control of a remote manipulator can be a difficult task due, in part, to a lack of useful feedback to the operator on the position of the manipulator with respect to its desired position, destination, or target object to be manipulated. For example, to control many remote manipulator systems, including the space shuttle remote manipulator system (SRMS), the operator relies largely on visual feedback from direct views through windows and indirect views from cameras. However, the visual information can be insufficient in providing the operator with adequate cues, due to obstructions, poor viewing angles, camera failures, or problems with resolution or camera control. Our first mode, the Manipulator Position Display (MPD) mode addresses these problems.

Another area of which poses concerns for the operator is avoiding undesired positions which cause joint limits or singularities. The operator may not get an indication that such a problem is developing until the problem has already occurred. For example, a warning light may indicate that a reach limit has occurred. Such indications do not always warn the operator ahead of time so that he/she can avoid the undesired position, or provide useful cues to tell the operator how to get out of the situation once it has occurred. Our second mode, the Joint Angle Display (JAD) mode was designed to help alleviate some of these control difficulties.

A third area of interest is force feedback through sensory substitution. Force feedback has been shown to be preferable to non-force feedback in many teleoperation studies.[1] However, providing force reflection in the form of a force to the operator's arm and hand muscles can have its disadvantages. Systems that provide force feedback are often bulky master/slave manipulators that are impractical in many environments. Further, presenting force feedback to the operator's hand or arm in the presence of even small time delays has been shown to create operator induced instabilities. The third mode of the MMDS is the Sensory Substitution (SS) mode and addresses these issues.

At the time of the writing of this paper, the MPD mode has undergone testing and is further along in the development cycle than both the JAD mode which is in its initial development and the SS mode which is still in its design phase.

2. Manipulator Position Display (MPD) Mode

The MPD mode provides six degree of freedom hand controller positioning cues to the operator in a graphical format. This mode was designed to help alleviate the problems associated with poor visual feedback caused by obstructions, poor viewing angles, poor resolution, camera control, or camera failure. The MPD mode relies on six degree of freedom information obtained from manipulator sensors, such as joint position encoders, or, if available, a computer based vision system which can calculate current position relative to a target or desired position. The MPD's algorithms perform the necessary calculations and provide the operator with "fly-from" or “fly-to” cues that alleviate from the operator the burden of calculating the appropriate system inputs.[2]

In order to operate effectively, the MPD mode requires knowledge of the current and desired (or target) positions. The current position of the manipulator arm can be obtained through real time position data from the system sensors (encoders or vision system) in six degrees of freedom. The desired position of the arm in six degrees of freedom can be entered into the MPD program if they are known aprioi, or can be obtained from vision system or telemetry data if such data are available. With this knowledge, the MPD mode can present the deviation or error that exists in each degree of freedom to the operator in an easy to use format. The MPD mode not only has applications for the space manipulators, but also for other human-machine applications (aircraft, deep sea manipulators, toxic waste cleanup, etc.) which require the operator to control multi-degree of freedom systems under limited viewing conditions when the desired target points can be identified.

2.1 MPD Mode Display for the SRMS - The Rotational/Translational Display (RTD)

The display to be used by the operator in MPD mode can be tailored to the application area if necessary. As an example, we will examine the Rotational/Translational Display (RTD) which is the MPD mode display designed for astronauts who control the Space Shuttle Remote Manipulator System (SRMS).

Figure 1 shows the format of the RTD.[3] The RTD separates the rotational and translational cues by depicting those cues through the motion of two separate objects. Two separate hand controllers are used by the astronauts to control the SRMS: 1) a Translational Hand Controller (THC) to control all translational motions, and 2) a Rotational Hand Controller (RHC) which is used to control all rotational motions. The RTD was designed so that one object on the display would correlate exclusively to the translational inputs on the THC, while the second object would correlate exclusively to rotational inputs on the RHC. This concept and the format of the display was developed by working directly with several astronauts. An explanation of how the RTD works and a summary of its features follows.

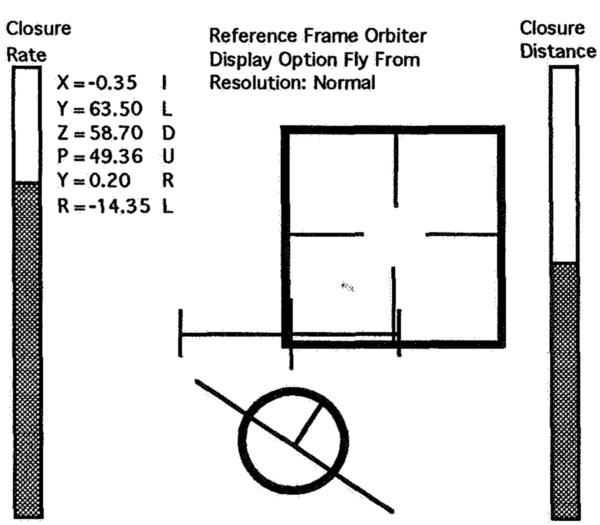

Fig. 1. Rotational/Translational Display (RTD) Format

The line in the center with the three tick marks in Fig. 1 is stationary and acts as the reference line. The operator drives the translational cues using the square with the tick marks shown. Deviation in Z-translation (up an down motion) is depicted by the square being above or below the reference line, while Y-translation deviation (side to side motion) is shown by the square being to the left or right of the center of the reference line. For X-translation (in and out motion), the operator relies on the size of the square relative to the length of the reference line.

For rotational cues the operator looks to the circular object shown in Fig. 1. The position of the circle with respect to the reference line provides the rotational deviation information. If the circle is above or below the reference line, a deviation in pitch exists. A deviation in yaw is depicted by the circle being to the left or right of the center of the reference line. Roll cues are provided by the orientation of the extended line running through the center of the circle and the shorter line in the center of the circle. If those lines are tilted to the left or to the right, then a deviation in roll exists.

On either side of the display are bar graphs which represent the closure rate, on the left, and the closure distance, on the right. These cues become useful when the tip of the manipulator is approaching its final destination. In addition, the operator is provided with a digital readout of the deviations in each of the six degrees of freedom. This digital readout can be seen in the upper left hand corner of Figure 1, and would be helpful in the final stages of a task to ensure that the deviations are within the desired limits (i.e. close to zero).

The RTD also includes a number of other features to provide the operator better assessment of the manipulator's position. One of these features is the highlighting of cues. This feature becomes most useful when the manipulator is reaching its target position and the RTD cues are converging on the stationary reference line. A task will usually have defined tolerance limits for each degree of freedom within which the manipulator is considered to be at its desired final position. Based on this information the highlighting feature indicates to the operator when the manipulator is within the defined limit for each degree of freedom. This indication is achieved by increasing the width of specific lines on the rotational and translational cues. For example, when the position of the manipulator is within the specified range in the X-axis the square becomes bolder than the other lines. When all of the lines which comprise the translational cue are bold, the operator will know that the manipulator tip is within tolerance in the X, Y, and Z axes. The rotational cues work similarly. For example, the circle becomes bold when the manipulator's attitude is within the yaw limit. As with the translational cue, when the manipulator attitude is within limit in yaw, pitch, and roll the entire rotational cue will be bold. Fig. 1 shows an example of the bold feature indicating that the X-axis and the yaw axes are within range. The tolerances can be set to different values for each degree of freedom and for each task.

In addition to the highlighting feature, the RTD display also provides color cues to help distinguish between the translational and rotational cues, and the stationary reference line. The use of color is useful when the manipulator position is close to its final destination and it can be difficult to differentiate between the translational cue, rotational cue, and the reference line. In the current MPD implementation the translational cue is drawn in red, the rotational in green and the reference line in white.

The RTD also displays hand controller Direction Cues which provide the operator with cues for the necessary hand controller deflections. The Direction Cues can be seen in Figure 1 as letters following the deltas in the upper left-hand corner of the display. The letters I or O are used to indicate in or out deflection of the translational hand controller, L or R for left or right deflection of the translational hand controller, and U or D for up or down deflection of the translational hand controller. For the rotational Direction Cues the letters U, D, L , and R are used in the same way as with the translational Direction Cues. With Direction Cues the operator is presented with clear indications of the necessary hand controller deflections eliminating the possibility of unnecessary and potentially dangerous movement of the manipulator.

The RTD also provides the operator with a choice for displaying the cues in fly-from (outside-in) or fly-to (inside-out) formats. [4] At the beginning of each task the operator is given the choice of which convention to use. Once the selection is made, the RTD lists the selection being used in the top center part of the screen as shown in Figure 1.

The RTD also has the capability to select between the different coordinate frames in which the manipulator position and attitude can be commanded. The RTD can be operated in three different coordinate frames: orbiter, end effector, and payload. These choices correspond to the reference frame options for commanding the SRMS on the space shuttle. Once selected the choice is displayed in the top center part of the main display screen above the fly-from fly-to selection (see Figure 1). The choice of coordinate frames can be modified to include any number of frames.

To quantify the effectiveness of the RTD, experiments with human operators were conducted. The RTD was presented to four trained and experienced test subjects on a GRID 1660 laptop computer. A space shuttle SRMS task was simulated using the Manipulator Analysis - Graphic, Interactive, Kinematic (MAGIK)[5] simulation system which runs on Silicon Graphics computers. The task was a space station assembly task, which focused on the installation of a Pressurized Mating Adapter (PMA) to a space station module. The experimental results concluded that using the RTD significantly improved operator performance by 33% over performing the same task without the use of the RTD.[3,6]

The RTD is a useful tool for SRMS operations. Changes can be made to the RTD to tailor an MPD mode display for applications other than SRMS such as undersea, rovers, or toxic waste cleanup.

3. Joint Angle Display Mode

Another area of telerobotics operation where the operator can use assistance is the avoidance of unwanted joint positions such as joint limits or singularities. Reaching such limitations could shut down the system with a software stop (soft stop) or a mechanical hardware stop (hard stop). This type of situation could force the operator to control the manipulator in a single joint mode where each joint must be driven individually to alleviate the problem. The goal of the Joint Angle Display (JAD) is to present the operator with graphical cues which provide information on the current position of each joint relative to software stops and hardware stops.

The JAD is comprised of a set of bar graphs which represent the position of each joint of a manipulator. The bar graphs are updated on a real-time basis using data from the position sensors at each joint. The JAD mode has three submodes: 1) nominal operations, 2) joint limits, and 3) single joint operations.

3.1 Nominal Operations Display Submode

The nominal operations submode display provides the current joint positions to the operator. As can be seen in Figure 2, each joint is identified at the top of each bar graph: SY = shoulder yaw, SP = shoulder pitch, EP = elbow pitch, WY = wrist yaw, WP = wrist pitch, WR = wrist roll. As the position of the joints change the bar graphs are updated keeping the operator informed of the position of each joint. Used in conjunction with the MPD mode display, the JAD provides the operator with sufficient information to keep the manipulator from reaching unwanted joint positions while being driven to its final POR.

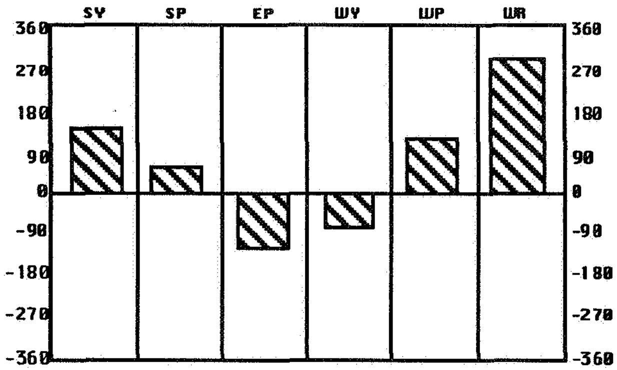

Figure 2. Nominal Operations Joint Angle Display

3.2 Joint Limits Display Submode

The second submode of the JAD includes all the features of the first submode plus cues to indicate the location of the task specific joint limitations. These limits are specific to different tasks being performed by the manipulator and can be used to keep the operator from positioning the manipulator in undesired areas. As can be seen in Figure 3 the joint limits are indicated by the small triangles to the right of each bar graph. Further, when a joint limit is reached the pattern or color of the associated bar graph can also change as an added cue for the operator. This feature eliminates the burden on the operator to recall the limit of each individual joint when trying to identify which joint has reached its limit. In addition, this display can also emit an audible tone when any joint reaches a limit. By including the audible tone the operator will be notified of a joint limit error without having to constantly monitor each joint.

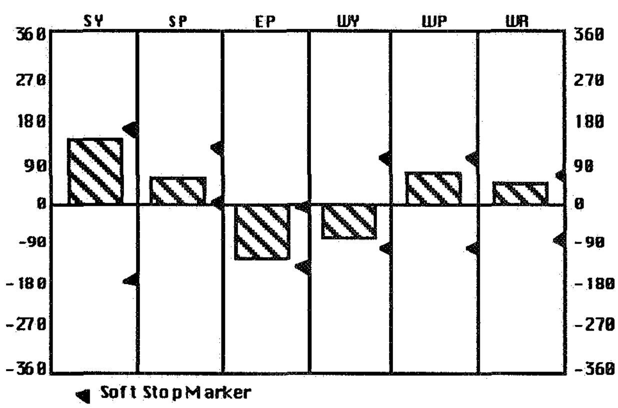

Figure 3. Joint Limits in the Joint Angle Display

3.3 Single Joint Operations Display Submode

Another application for the JAD mode will be single joint operations when the operator needs to drive the arm through a sequence of single joint movements. This operational scenario could occur during failure modes which make controlling all joints concurrently impossible. During these operations, the Single Joint Operations submode will not only provide the operator with information on the current joint positions and joint limits, but will also provide the operator with operational cues. These cues will include the amount of deflection needed for each joint, and the joint sequence. The sequence is shown by highlighting the bar graph associated with the joint to be commanded while the desired position is indicated by a triangle on the left-hand side to the bar graph. Once the joint reaches the desired position its bar graph is displayed normally and the bar graph associated with the next joint in the sequence is highlighted. Figure 4 provides an example of the Single Joint Operations Submode display. In this example the display indicates that the Wrist Pitch joint should be moved to -86 degrees.

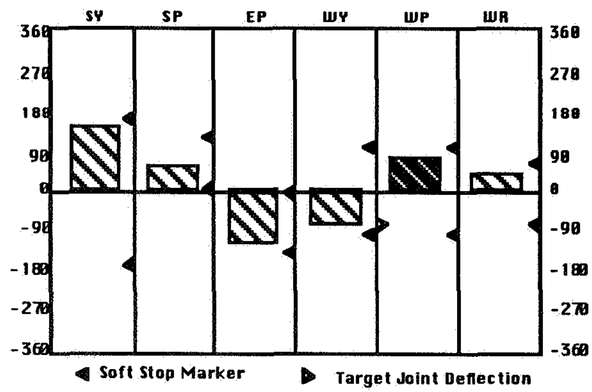

Figure 4. Wrist pitch joint indication.

4. Sensory Substitution Mode

To provide force feedback information to the operator, force reflection is the method used for most master-slave systems. Force reflection has had a long history of success. For example, Hill and Salisbury[7] found in their experiments that with force feedback task completion times were significantly shorter than without force feedback for peg-in-hole tasks. However, providing force reflection in the form of a force to the operator's arm and hand muscles can have its disadvantages. Systems that provide force feedback are often bulky master/slave manipulators that are impractical in many environments. Further, presenting force feedback to the operator's hand or arm in the presence of even small time delays has been shown to create operator induced instabilities. Ferrell[8] suggested that the advantages of force sensitivity could be maintained in the presence of a time delay if the force feedback were substituted through the auditory or tactile modalities, and that a tactile display to the active hand might be especially compatible. The third mode of the MMDS is the Sensory Substitution (SS) mode and addresses these issues.

Bach-y-Rita, Webster, Tompkins, and Crabb[9] define sensory substitution as "the provision to the brain of information that is usually in one sensory domain (for example visual information via the eyes and visual system) by means of the receptors, pathways and brain projection, integrative and interpretative areas of another sensory system, (for example visual information through the skin and somatosensory system). Some examples include sign language for the deaf, and Braille for the blind." Sensory substitution has been successfully used for many years in helping people who are fully or partially deficient in one or more of their sensory systems, for example, sensory aids for the blind or deaf.[10]

4.1 Tactile and Auditory Displays

To provide the sensory substitution information, we are concentrating on tactile and auditory feedback devices for the operator. The tactile, in particular vibrotactile, and auditory modalities are of interest for several reasons. Such displays might be particularly useful for presenting force information because they provided non-reactive representations of force feedback. Non-reactive means sense modalities that do not induce operator movements like force reflection does when providing force information.[11] Such movements may be undesirable in certain situations, and can cause instabilities in the presence of a time delay. They are desirable for generic task information as well, because the auditory and vibrotactile modalities can present information while not placing any extra burden on the operator's visual system which is normally intently viewing the remote task environment via television monitor.

Vibrotactile and auditory displays may also provide cost benefits by reducing the need for expensive bilateral force reflecting manipulators. Further, auditory and vibrotactile displays may also reduce the need for expensive or complicated visual systems. Massimino and Sheridan[1] showed that force feedback could decrease the need for visual feedback, since force feedback combined with low frame rate conditions (3 frames per second) provided performance that was comparable to performance under high frame rate conditions (30 frames per second) without force feedback. In addition, Bliss, Hill, and Wilber[12] concluded that the utility of tactile feedback increased under poor visual conditions, and provided highly useful information that required a relatively low bandwidth channel. Thus a potential benefit of vibrotactile or auditory feedback is a possible reduced need for high quality visual feedback which could lead to decreased cost of teleoperation.

We are currently developing auditory and tactile displays to present manipulator force and position information to the operator. These displays will be incorporated into our multi-mode system to provide the operator with an integrated visual, auditory, and tactile feedback display system.

5. Conclusions

The MMDS can be expected to provide significant operational benefits that include providing the operator with useful manipulator position information when viewing conditions are constrained, assisting with recognizing and avoiding unwanted manipulator position, and providing force information under conditions which would normally make the presentation of such information impractical. The MMDS can also reduce operator workload, reduce training time, and assist the operator with performing unscheduled or unpracticed procedures. The MMDS has space based application for the space shuttle and the space station as well as for ground control of space based manipulators. It is a generic system which can be utilized for dual use application areas such environmental, hazardous waste, nuclear, and undersea remote manipulation environments.

6. References

1. Massimino, M.J., and Sheridan, T.B. Variable Force and Visual Feedback Effects on Teleoperator Man/Machine Performance. Proceedings of the NASA Conference on Space Telerobotics. Pasadena, CA, January 31-February 2, 1989.

2. D.W. Collins, "Payload Deployment and Retrieval System Overview Workbook," NASA NASA TD383, NAS9-18000, NASA Johnson Space Center, Mission Operations Directorate, Space Flight Training Division, Houston, TX, Feb. 1988.

3. M.J. Massimino, M.F. Meschler, and A.A. Rodriguez, "Human-Machine Interface Aids for Space Telerobotics," 44th Congress of the International Astronautical Federation, Graz, Austria, Oct. 1993, paper # IAF/IAA-93-G.3.154.

4. L. R. Young, "Human Control Capabilities," Bioastronautics Data Book, Second Edition, pp 751-806, NASA Scientific and Technical Informarion Office, Washington, D. C., 1973.

5. R.G. Boettger, K.E. Harvey, A.S. Mediavilla, W.C. O'Donnell, "Manipulator Analysis - Graphic, Interactive, Kinematic (MAGIK) Version 5.4 User's Guide", NASA TM-5.24.11-25, NASA Johnson Space Center, Automation and Robotics Division, Houston, TX, Sept. 1992.

6. M. Massimino and M. Meschler, "Experimental Results Using a Manipulator Position Display as a Human-Machine Interface Aid for Controlling Space Robotic Tasks," AIAA Space Programs and Technologies Conference and Exhibit, Huntsville, AL, Sept. 1993, paper # AIAA 93-4114.

7. Hill, J.W. and Salisbury, J.K. Study to Design and Develop Remote Manipulator Systems. Annual Report, NASA Contract NAS2-8652, Nov., 1977.

8. Ferrell, W.R. Delayed Force Feedback. Human Factors. Vol.8, No.5, October, 1966. pp.449-455.

9. Bach-y-Rita, P., Webster, J.G., Tompkins, W.J., and Crabb, T.. Sensory Substitution for Space Gloves and for Space Robots. In Proceedings of Workshop on Space Telerobotics, Vol.2.,pp.51-57.

10. Mann, R.W. Technology and Human Rehabilitation: Prostheses for Sensory Rehabilitation and/or Sensory Substitution. Advances in Biomedical Engineering, Vol. 4, 1974, pp. 209-353.

11. Massimino, M.J. and Sheridan, T.B. Sensory Substitution for Force Feedback in Teleoperation. Analysis, Design and Evaluation of Man-Machine Systems 1992, Selected Papers from the 5th IFAC/IFIP/IFORS/IEA Symposium, The Hague, The Netherlands, June, 1992, H.G. Stassen, Editor, Oxford: Pergamon Press, 1993.

12. Bliss, J.C., Hill, J.W., and Wilber, B.M. Tactile Perception Studies Related to Teleoperator Systems. NASA-CR-1775, Stanford Research Institute, Menlo Park, CA.