"A MULTI-MODE MANIPULATOR DISPLAY SYSTEM FOR CONTROLLING REMOTE ROBOTIC SYSTEMS"

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Abstract

The objective and contribution of the research presented in this paper is to provide a Multi-Mode Manipulator Display System (MMDS) to assist a human operator with the control of remote manipulator systems. Such systems include space based manipulators such as the space shuttle remote manipulator system (SRMS) and future ground controlled teleoperated and telescience space systems. The MMDS contains a number of display modes and submodes which display position control cues position data in graphical formats, based primarily on manipulator position and joint angle data. Therefore the MMDS is not dependent on visual information for input and can assist the operator especially when visual feedback is inadequate. This paper provides descriptions of the new modes and experiment results to date.

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.

The Multi-Mode Manipulator Display System (MMDS) is being developed by MDA to alleviate some of these difficulties. The current design of the MMDS consists of two major modes: 1) the Manipulator Position Display (MPD) mode, and 2) the Joint Angle Display (JAD) mode. At the time of the writing of this paper, the MPD mode has undergone testing and is further along in the development cycle than the JAD mode which is in its initial development.

2. Manipulator Position Display (MPD) Mode

The Manipulator Position Display mode consists of two sub-modes: 1) Rotational/Translational (R/T) Submode, and 2) MPD Pilot Submode. The two submodes of the MPD were designed to help alleviate the problems associated with poor visual feedback caused by obstructions, poor viewing angles, poor resolution, camera control, or camera failure. This can be done because the MPD does not rely on visually obtained information as a source of input, but rather on six degree of freedom position information data from the manipulator system sensors (for example, joint position encoders).

Further, with the MPD displays, six degree of freedom position cues are displayed to the operator in a graphical format. The MPD displays the six degree of freedom cues concurrently. In addition, the MPD's algorithm performs the necessary calculations and provides the operator with "fly-from" or "fly-to" cues that alleviate the burden of calculating the appropriate system inputs from the operator. [1]

The MPD needs to know the current and desired (or target) positions. The current position of the manipulator arm can be obtained through real time position data from the manipulator arm in six degrees of freedom. The desired position of the arm in six degrees of freedom needs to be identified and entered into the MPD program. With this knowledge, the MPD displays can present the deviation or error that exists in each degree of freedom to the operator in an easy to use format. The MPD displays not only have applications for the SRMS, but also for other human-machine applications (aircraft, deep sea manipulators, nuclear environment, etc.) which require the operator to control multi-degree of freedom systems under limited viewing conditions when desired target points are known.

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The experiments conducted with the two submodes of the MPD mode showed that using either submode significantly improved operator performance (by 25 to 33%) over performing the same manipulation tasks without the use of the MPD submodes.[2,3]

2.1 Rotational/Translational Submode

Figure 1. shows the format of the Rotational/Translational (R/T) Submode of the Manipulator Position Display mode.[3] The Rotational/Translational Submode separates the rotational and translational cues to be represented by the motion of two separate objects. This submode was designed so that one object on the display would correlate exclusively to the translational inputs on the hand controllers, while the second object would correlate exclusively to rotational inputs on the hand controllers.

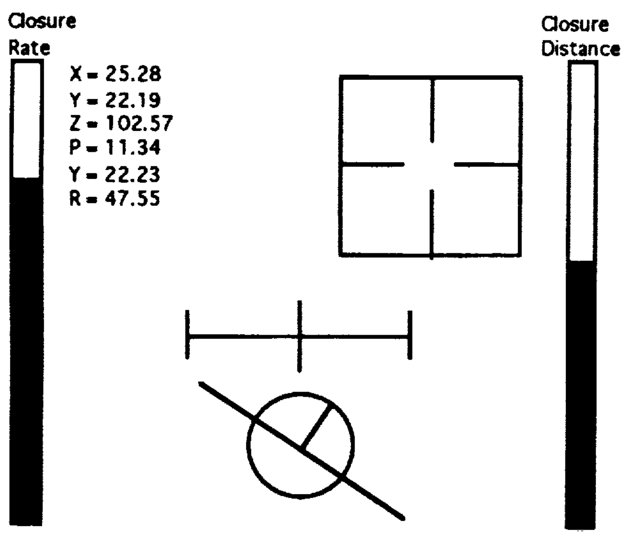

Fig. 1. MPD Rotation/Translation Submode Format

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 in Fig.1. Deviation in Z-translation is depicted by the square being above or below the reference line, while Y-translation deviation is shown by the square being to the left or right of the center of the reference line. For X-translation, the operator relies on the size of the square relative to the length of the reference line. For rotational cues the operator would look to the circular object shown in Fig. 1. The position of the circle with respect to the reference line provided the rotational deviation information to the operator. 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.

2.2 MPD Pilot Submode

The format of the MPD Pilot Submode of the Manipulator Position Display is shown in Fig. 2.[4] The MPD Pilot Submode got its name because it utilizes cues, such as a yaw ball and a pitch horizon line, similar to those found in aircraft. The line in the center with the three tick marks is stationary and acts as the reference line. The operator drives five of the six position/orientation cues to that reference line, all except the yaw cue which is shown separately at the bottom of the display.

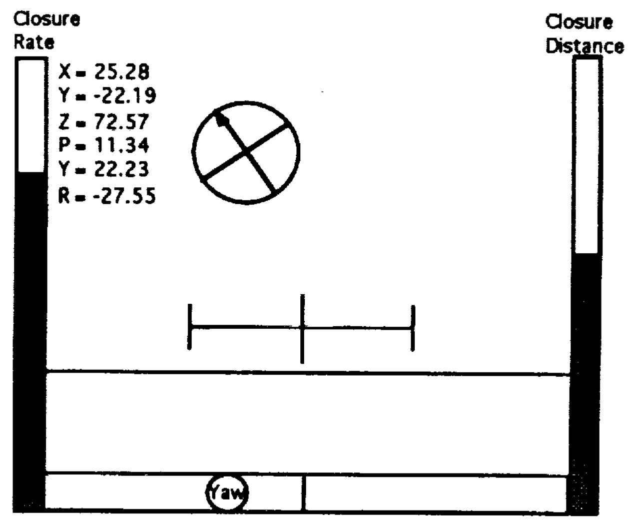

Fig. 2. MPD Pilot Submode Format.

All deviations in the translational degrees of freedom are displayed by the circle with the crosshairs inside of it. If the crosshairs are to the left or right of the center of the reference line, a deviation in Y-translation exists. A deviation in Z-translation is depicted with the circle and crosshairs being either above or below the reference line. Errors in X-translation is depicted as a size difference between the circle with crosshairs and the length of the reference line. For rotational cues the operator would look to the yaw ball at the bottom of the display, the horizontal pitch line (shown just below the reference line in Fig. 2), and the orientation of the crosshairs in the ball for roll information. The error in the yaw degree of freedom are shown by the yaw ball in Fig. 2 being to the left or right of center. Pitch error is shown by the horizontal pitch line being above or below the reference line. For roll cues the operator uses the orientation of the crosshairs inside the ball.

In addition, for both of the submodes discussed, 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 Figs. 1 and 2, and is helpful in the final stages of a task to ensure that the deviations are within the desired limits (i.e. close to zero).

Both submodes also contain two bar graphs on either side. The bar graph shown on the left of Figs. 1 and 2 provides rate information, and the bar graph on the right of Figs. 1 and 2 provides the absolute closure distance between the current manipulator position and the desired manipulator position. This information can be particularly helpful to control the rate of movement based on the distance from the target location. For example, if the manipulator were far from the target location the operator would probably want to moving faster than if the manipulator was very close to the target location.[5,6]

2.3 Experimental Results with the MPD Mode

To quantify the effectiveness of the two submodes of the MPD described in the previous sections, experiments with human operators were conducted. The MPD display submodes were 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) 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.

Three experimental conditions were tested: 1) performing the task with the aid of the Rotational/Translational Submode of the Manipulator Position Display, 2) performing the task with the aid of the MPD Pilot Submode of the Manipulator Position Display, and 3) performing the task without the aid of the MPD display mode. For all three experimental conditions the operators were given the clearest available camera view of the task (simulated by the MAGIK system) [7]. In addition, the operators were also given a digital readout of the position of the manipulator in each degree of freedom through a simulation of the SRMS display panel. During the experimental condition of performing the task without an MPD display, this digital position information was critical for the final steps of the task when the camera view became less helpful.

Each test subject completed training for performing the task without the MPD and with each submode of the MPD. Training ended when the test subject's performance times reached steady values and learning curves flattened. Three separate experimental sessions were conducted for each subject. During one experimental session, the subject performed the task without the MPD display , in another session the subject performed the task with the MPD Pilot Submode, and in a third session the subject performed the task with the Rotational/Translational Submode. At the start of each experimental session, each subject was given warm-up trials and then six to ten data trials were conducted. The subject could end an experimental trial when the deviation in each translational degree of freedom was less than 1 inch, and the deviation in each rotational degree of freedom was less than 0.5 degrees.

The mean task times for performing the tasks under the three experimental conditions are shown in table 1.

Pilot Submode	No MPD	R/T Submode
3.9 min	5.2 min	3.5 min

Table 1. Mean task times.

Fig. 3 shows the total average task times calculated across all of the four test subjects. The total mean task time averaged for all four test subjects was 3.9 minutes with a mean standard error of 0.12 minutes when using the MPD Pilot Submode , 5.17 minutes with a mean standard error of 0.19 minutes when not using the MPD, and 3.54 minutes with a mean standard error of 0.14 minutes when using the Rotational/Translational Submode. Therefore, the Rotational/Translational Submode provided an average improvement of approximately 33% while the MPD Pilot Submode provided an average improvement of approximately 25%. These results were statistically significant to the 99% confidence level.

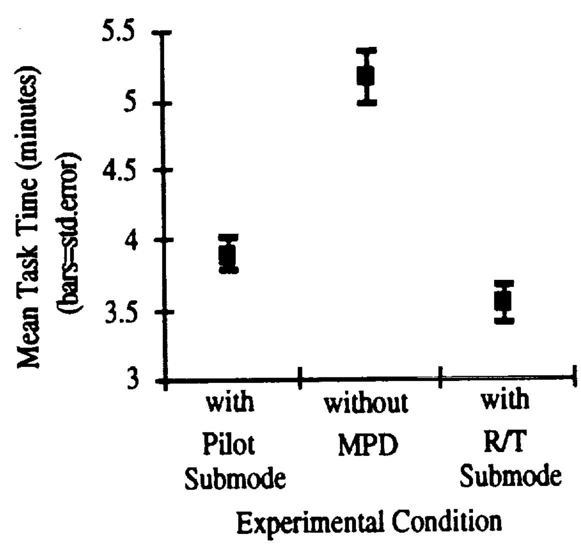

Fig. 3. Average of experimental results for all test subjects.

A statistical analysis with a series of paired t-tests showed that using the MPD Pilot Submode significantly improved operator performance at the 99% confidence level ($t(30)=7.44$, $p<0.01$). A series of t-tests were also conducted to determine the statistical significance of using the Rotational/Translational Submode versus not using the MPD. As was found with the MPD Pilot Submode, the Rotational/Translational Submode significantly improved operator performance at the 99% confidence level ($t(30)=7.41$, $p<0.01$). The statistical analysis of the results of using the Pilot Submode versus using the Rotational/Translational Submode produced differing conclusions based upon individual test subject performance. Test subjects #1 and #3 performed significantly better with the Rotational/Translational Submode than with the Pilot Submode. However, for test subjects #2 and #4, there was no significant performance difference between using the Rotational/Translational Submode versus using the Pilot Submode. The total average over all 4 test subjects did show a significant performance advantage with the Rotational/Translational Submode over the MPD Pilot Submode ($t30)=2.06$. $p<0.05$).

2.4 Advanced Features of the MPD

As a result of the experiments described above and comments from astronauts, mission designers, and astronaut trainers, a number of recommendations for improving the MPD were gathered. These recommendations have resulted in the implementation of a number of new features. The following section describes each of the new features and their benefits.

2.4.1 Highlighting

One advanced feature is highlighting cues to help the operator distinguish between the lines which represent the rotational and translational cues, and the stationary reference line at the center of the screen. This feature becomes most useful when the manipulator is reaching its target position and the operator is trying to align the cues to the stationary reference line. This is one of the most critical phases of any operation.

For each task there are 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 a highlighting feature was implemented which 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 when the manipulator position and attitude are within the specified range. For example, when the Point of Resolution (POR) of the manipulator is within the specified range in the X-axis (see figure 6-8) the square, in the R/T Submode, will become bolder than the other lines. In turn, when the POR of the manipulator is within tolerance in the Y-axis the vertical lines in the translational cue will become bolder. And finally, when the POR is within the limit in the Z-axis, the horizontal lines of the translational cue become bold. Once 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.

For the rotational cues in the R/T Submode, the circle becomes bold when the manipulator's POR is within the yaw limit. The horizontal line drawn through the circle is made bold when the pitch limit is satisfied. And the vertical roll indicator is made bold when the POR is within the roll limit. As with the translational cue, when the manipulator POR is within limit in yaw, pitch, and roll the entire rotational cue will be bold. Fig. 4 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. This feature is also implemented in the MPD Pilot Submode.

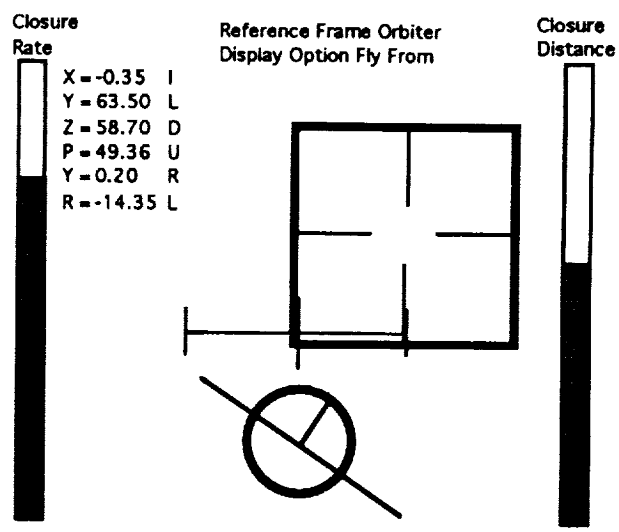

Fig. 4. MPD highlighting feature.

Another benefit of using line width as an indication of reaching final position is the ability to reach the desired position in any one axis regardless of where the cues are on the screen with respect to the reference line. For instance, in the event that a particular translational axis needs to be aligned before the other axes this can be done without the translational cue being lined up with the stationary reference line. This occurs when a payload must be centered in the X and Y axes before being lowered into the shuttle bay. During such a task the operator would have to adjust the size of the square to coincide with the length of the reference line without having the translational cue over the reference line. Without the added feature this would be accomplished by referring to the deltas being displayed on the upper left-hand corner, recalling the defined limit for each axis, and watching the translational cue. With the added feature the operator need only concentrate on the translational cue receiving a visual signal when the POR is within range for the desired axis(in this example the X-axis).

2.4.2 Color Cues

In addition to the highlighting feature, the MPD display now 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 POR is close to its final destination as shown in Fig 5. As can be seen in the figure 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.

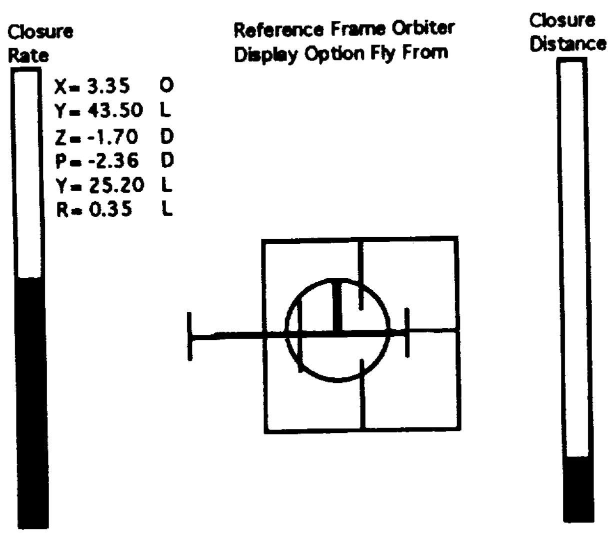

Fig. 5. MPD Display need for color cues.

Color cues are also being considered in conjunction with the highlighting feature to give the operator information on the proximity to the final destination. The idea is to define a range, like the limits described in the previous section, which when entered by the manipulator POR would cause the translational and rotational cues to change color. This would supply the operator with a visual cue that the manipulator POR is reaching its destination and in turn the hand controller inputs should be reduced in order avoid going beyond the desired final position. Once the previously described final limits are reached, the translational and rotational cues' colors can again be changed as the lines get bold. In this way the operator is given two signals that the manipulator has reached the final POR, bolder lines and change in color. [9]

2.4.3 Direction Cues

In the original implementation of the MPD, the deltas between the current and final POR positions were displayed as signed numbers in the upper left-hand corner of the screen. The sign of the numbers is provided as an indication of the direction in which the delta exists. In Fig. 5 this can be seen in the Z-axis and pitch digital delta readouts. This approach required the operator to mentally transform the sign cue to the coordinate frame in which they are working, then figure out the corresponding hand controller deflections required to compensate for the deviation. However, what usually occurs is that the operator inputs the wrong direction based on the sign delta.

To alleviate this difficulty the MPD includes a feature referred to as "Direction Cues". Direction Cues supply the operator with instructions of the necessary hand controller deflections to remove the deltas in each degree of freedom. The Direction Cues can be seen in Fig. 5 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. Fig. 5 shows the display signaling the operator to deflect the translational hand controller out, left, and down and the rotational hand controller down, left, and left for the pitch, yaw, and roll axes respectively. With the addition of Direction Cues the operator is presented with straight forward indications of the necessary hand controller deflections eliminating the possibility of unnecessary and potentially dangerous movement of the manipulator.

2.4. 4 Fly-To/Fly-From Option

The original version of the MPD displays used what is referred to as "fly- from," or outside-in, convention to show the deviation between the current manipulator POR position and the desired final position. In the fly-from convention the objective is to input the necessary hand controller deflections to move the graphical cues from their current positions to a specified reference point in the display. In the MPD displays the reference point is the stationary reference line in the center of the screen. As operators with varying backgrounds used the MPD displays two points were made about the utilization of the fly-from convention.

First, it was not obvious from the information presented by the MPD displays that a fly-from convention was being used. And secondly, not everyone is used to the fly-from convention. Some operators are more comfortable with the "fly-to", or inside-out, convention. In the fly-to convention the objective is to deflect the hand controllers in such a way as to move a specified reference point, the stationary reference line, to the current position of the graphical cues. As the hand controller inputs are generated the graphical cues move towards the reference line giving the illusion that the reference line is moving. [10]

Having reached the conclusion that neither one of the conventions exhibit any inherent advantages, the MPD display now gives the operator a choice of using either option. At the beginning of each task the operator selects whether the graphical cues are shown in the fly-to or fly-from convention. Once this selection is made, the MPD displays the option in the top center part of the screen as can be seen in Fig. 5. This new feature gives the flexibility to use the display in the convention which is most comfortable to the operator and also makes the current selection obvious at all times.

2.4.5 Coordinate Frame Selection

The last addition to the original MPD display is the capability to select between the different coordinate frames in which to command the manipulator POR. Originally the commands where all based in the orbiter coordinate frame which is shown in Fig. 6.

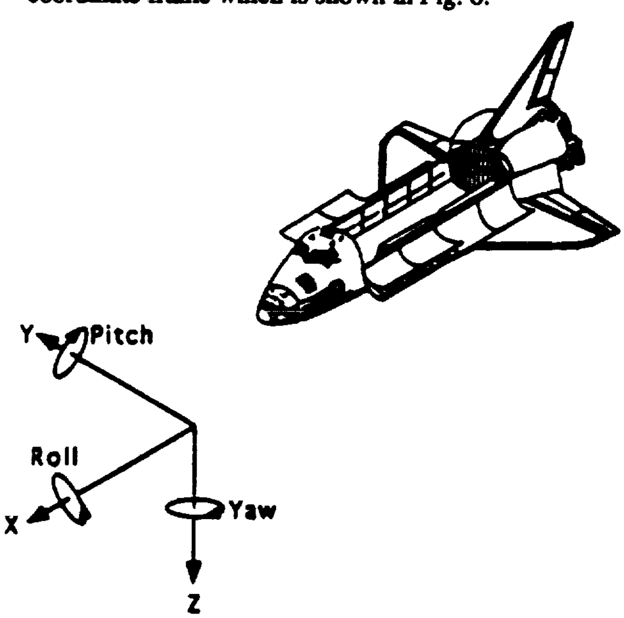

Fig 6. Space Shuttle coordinate reference frame.

With the addition of the coordinate frame selection feature the operator now has a choice between orbiter, end effector, and payload coordinate frames. In the case of the space shuttle, this is a major improvement over the information currently displayed in the aft flight deck which is always in orbiter reference mode. An example of an end effector coordinate frame is depicted in Fig. 7.

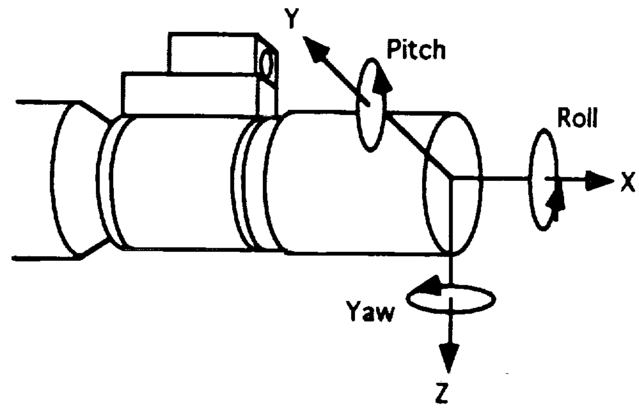

Fig. 7. End effector coordinate frame.

The payload coordinate frame is different for each payload and can sometimes coincide with either the end effector or orbiter coordinate frames. Fig. 8 shows an example of a payload coordinate frame.

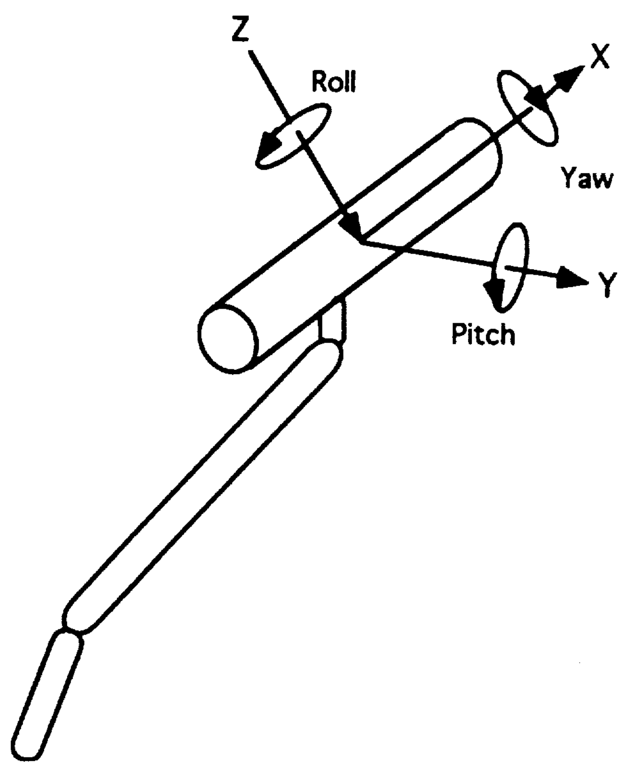

Fig. 8. Payload coordinate frame.

The coordinate frame selection feature provides consistency in the way the graphical cues display changes in the different axes. For example, in the R/T Submode movement in the X-axis is always depicted as changes in the size of the square of the translational cue. Motion in the Y-axis is always shown as a change in the translational cue's horizontal position on the screen. And motion in the Z-axis is always shown as a change in the translational cue's vertical position on the screen. The selected reference frame is displayed in the top center part of the screen (see Fig. 5). [11]

3. Joint Angle Display Mode

The second major mode of the MMDS is the Joint Angle Display (JAD) Mode. The JAD is comprised of a set of bargraphs which represent the position of each joint of a manipulator. The JAD mode has three submodes: 1) nominal operations, 2) joint limits, and 3) single joint operations.

3.1 Nominal Operations Submode

The nominal operations mode displays the current joint positions to the operator. For example, the SRMS has six joints as is shown in Fig. 9. Fig. 10 shows how the six joint values for the SRMS would be presented to the operator. Note that each joint in Fig. 9 is listed in Fig. 10. Each bar graph represents the current joint angle. The bar graphs are updated in real-time based on the changing encoder values at each joint.

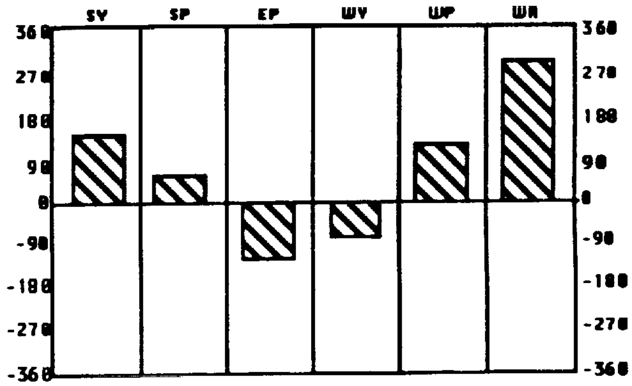

Fig. 10. Nominal operations Joint Angle Display

3.2 Joint Limits Submode

The second submode of the display will include all the features of the first submode plus cues to indicate the location of the joint limitations. As can be seen in Fig. 11 the joint limits are depicted by the small triangles to the right of each bar graph. For instance Fig. 11 shows that for the SY joint the joint limits are at ±180°. This display could 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. Having the features designed in this submode of the JAD provides the operator with a tool to avoid joint limits.

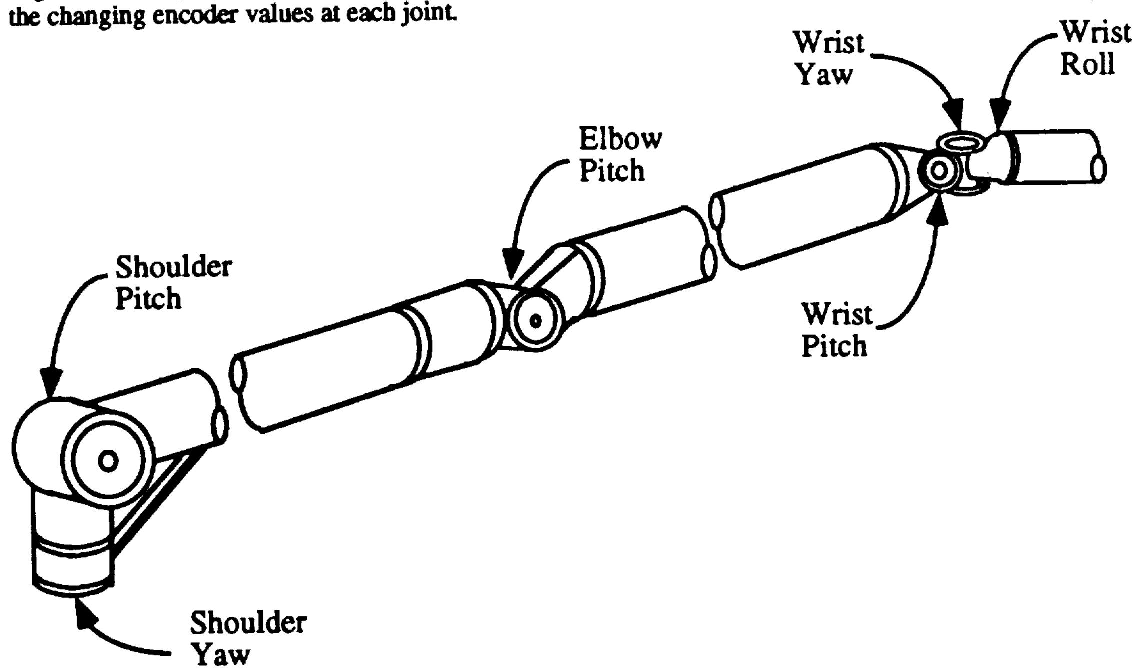

Fig. 9 SRMS Manipulator

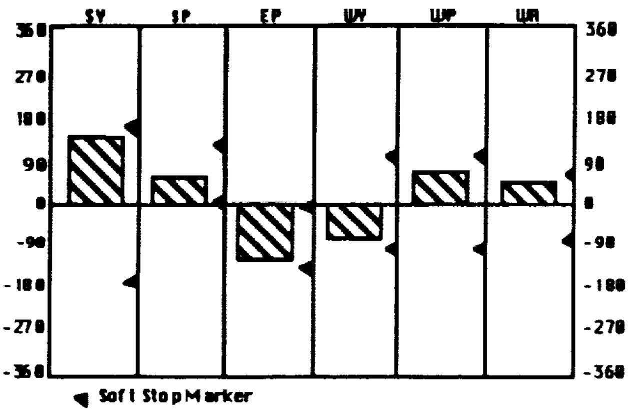

Fig. 11. Joint Limits in the Joint Angle Display

<u>3.3 Single Joint Operations Submode</u>

Another application for the JAD will be single joint operations when the operator needs to drive the arm one joint at a time. This operational scenario occurs on the space shuttle during failure modes which make controlling all joints concurrently impossible (for example, a hand controller failure). 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. One limitation of this display is, however, that the encoder data from the manipulator joints are needed to run the display and might not be available in the event of a failure.

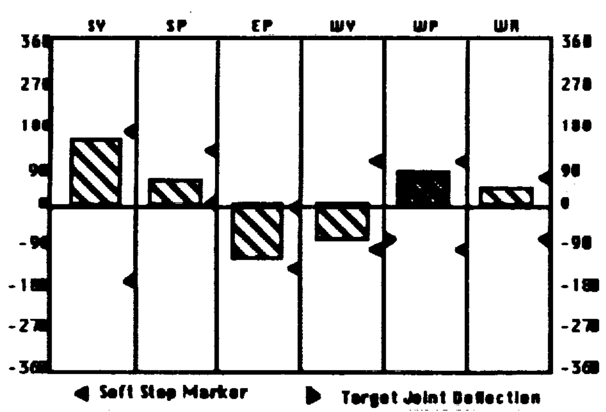

Fig. 12. Wrist pitch joint indication.

Fig. 12 provides an example of the Single Joint Operations Submode display. Fig. 12 indicates that the Wrist Pitch joint should be moved to -86 degrees. Once the operation in Fig. 12 is complete, the next step would be displayed.

<u>4. System Summary</u>

With the completely integrated MMDS the operator is supplied with a complete, concise, and flexible view of the state of the manipulator at all times. This complete view includes information on both the manipulator POR position through the use of the MPD displays, and the position of each individual joint through the use of the JAD. Using the MMDS, a typical grapple and unberth task with SRMS can be described as follows.

The operator begins the task using the MPD display of their choice, Pilot or Rotational/Translational Submode, in end effector coordinate reference frame and fly-from mode. As the operator maneuvers toward the grapple fixture, they can at any time switch to the JAD viewing the status of each joint and their proximity to any limits. Once the POR is within the predefined limits the translational and rotational cues are highlighted. At this time the payload is grappled and the operator switches to orbiter coordinate reference frame.

With the payload grappled a new target POR position is entered and the translational and rotational cues adjust to show the new deltas. The operator now begins to issue the appropriate hand controller deflections to move the manipulator towards the new destination. If at any point during the task a joint limit is reached, the JAD will sound an audible tone anunciating that such a limit has been reached.

Upon recognizing the joint limit alarm, the operator will switch to the JAD where he/she can rapidly identify the errant joint. The operator would then switch to single joint mode and command the wayward joint away from the limit using the JAD. Once the joint is backed away from the limit the operator can revert to the MPD display to reach the final POR.

Another task would be to berth the payload into the orbiter bay. Once again the new target position is entered and the translational and rotational cues adjusted to show the deltas. At this point the operator can use the payload coordinate reference frame to drive the payload into its berthed position. Once the final berthed position is reached the task is completed.

One final note with respect to the flexibility of the MMDS. At any time during the task described above the operator has the capability to choose between how and what information is displayed without having to restart the MMDS. The operator can switch between the MPD or JAD, Pilot or R/T Submode, and coordinate reference frames. This capability gives the operator the ability to command the manipulator in a way that is most suitable to their background and training.

5. Conclusions

Based on the development and experimental results presented in this paper, the MMDS can be expected to provide significant operational benefits including providing the operator with useful manipulator position information, reducing control problems associated with the poor viewing conditions, reducing operator workload, reducing training time, and assisting the operator with performing unscheduled or unpracticed procedures. The MMDS has space based application for the SSRMS space station as well as for ground control of space based manipulators. Its potential application areas will hopefully be expanded into environmental, hazardous waste, nuclear, and undersea remote manipulation environments.

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