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MARTIN MARIETTA

Docking Automation Related Technology Phase II Report

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AMMUNITION LOGISTICS PROGRAM

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FOR THE UNITED STATES
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DOCKING AUTOMATION RELATED TECHNOLOGY PHASE II REPORT

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EXECUTIVE SUMMARY

This report generalizes the progress for Phase II of the Docking Automated Related Technologies task component within the Modular Artillery Ammunition Delivery System (MAADS) technology demonstrator of the Future Armored Resupply Vehicle (FARV) project. This report also covers development activity at Oak Ridge National Laboratory (ORNL) during the period from January to July 1994.

The objective of Phase II is to demonstrate the basic functionality needed to autonomously dock the MAADS demonstration arm under computer control. In the current MAADS arm design, an additional subsystem to remotely measure the pose of the receiving port is needed to support autonomous docking. A pose measurement consists of the X, Y, and Z position coordinates and the roll, pitch, and yaw orientation angles of the intended docking port. The pose parameters are measured and supplied to the control system upon demand in order to calculate the desired approach path to the port.

A prototype system to perform remote pose measurement has been assembled and tested by ORNL engineers. A miniature video camera and image processing computer are used to implement the measurement function. The receiving port is simulated with a seven-sided box that resembles a house turned on its side. Infrared light-emitting diodes are located at each vertex of the "roof." The diodes are isolated from other objects in the camera view by image processing techniques. These diodes mark the outline of the target shape. The pose determination algorithm matches the fiducial markers in the video image with corresponding points on a rudimentary model of a polyhedron. Because the optical characteristics of the lens and dimensions of the target are known, the target pose can be calculated from the marker coordinates.

The measurement error in the Phase II system is approximately 1%. The dominant sources of error have been identified, and the accuracy should be improved as refinements planned for Phase III are implemented.

The measurement system has a graphical user interface to display the pose parameters to an operator. Simulated gauges display the absolute values of position and orientation on a cathode-ray tube screen. Relative positional information is presented via a "video game-like widget" that incorporates all six measurement parameters into a single graphical icon. The graphical interface has potential utility in monitoring the arm position for both manual and autonomous docking modes.

The video measurement system and its graphical display were demonstrated to representatives and guests of the Advanced Field Artillery System/FARV office on July 21, 1994, at ORNL.

In Phase III, now under way, the pose determination algorithm and its hardware and software implementation will be improved and refined but should still be considered prototypical. Whenever possible, the eventual operating environment of the measurement system will be considered in the design stage, but demonstrations of operation under battlefield conditions are not planned. The algorithm will be extended to match the target reference model with intrinsic image features such as edges and corners. The primary advantage of matching intrinsic features is that it can eliminate the need for active components such as illuminating markers on the docking port. The port is thus identifiable to the system by its geometric features and will not be illuminating markers. Both methods of model matching will be compared and evaluated.

The measurement system will be integrated with the MAADS arm in three incremental stages to demonstrate autonomous docking. The performance of the measurement system will be verified with (1) a computer-simulated robotic arm, (2) a table-top robotic arm, and (3) the MAADS arm.

1. INTRODUCTION

The U.S. Army is planning the next generation of battlefield artillery vehicles. The new vehicles are the Advanced Field Artillery System (AFAS), a self-propelled artillery system, and the Future Armored Resupply Vehicle (FARV), also a self-propelled vehicle to resupply the AFAS in the field. The FARV is envisioned to have a robotic resupply arm that can attach to a receiving port on the AFAS. In this configuration, ammunition can be transferred from the FARV to the AFAS through a motorized conveyor within the resupply boom.

The resupply operation is greatly dependent upon the skill of the boom operator to manipulate the boom into docking position. Computer simulations at the National Aeronautics and Space Administration have shown that computer-assisted or autonomous docking can improve the ability of the operator to dock safely and quickly.

A three-phase development effort in Docking Automation Related Technologies is under way at Oak Ridge National Laboratory. Phase I consisted of a 3-month feasibility study, beginning in June 1993, to determine if currently available technology would support autonomous guidance of a robotic arm. Phase II was a 6-month effort to develop machine vision hardware, culminating with a demonstration of the basic measurement functionality required for autodocking. Phase III is planned to feature incremental demonstrations of autonomous docking in increasingly realistic environments.

The objective of Phase II was to prove that the pose (position and orientation) of the receiving port can be accurately measured from a remote location. A vision-based remote pose determination method has been developed and implemented as part of the Modular Artillery Ammunition Delivery System technology demonstration arm. This system measures the 6-D.F. position and orientation of a target port with respect to a vision sensor. Robustness and measurement quality estimates have been incorporated into the design to give high accuracy as well as to prevent the reporting of large position errors. A summary of the algorithm and hardware used for implementation is given in Sect. 2. Initial test results are also described.

2. THEORY OF OPERATION

A point method based on a model of a polyhedral object is used to calculate the position and orientation (pose) of a target with respect to a camera. The model of the object is represented as surface faces, each of which is a convex quadrilateral with four vertices. Adjacent faces then share two vertices. From an image of the target object, points are extracted which represent the vertices of the object. These image points are then matched to the target vertices based on the convexity and adjacency constraints. Extraneous points at random locations that are not part of the target are sometimes mistakenly detected. The extraneous points arise from transient specular reflections that have characteristics similar to those of the true vertex points. The extraneous points will not, in general, provide a fit to the model and will be rejected. However erroneous matches are possible. Error checking performed during the subsequent pose calculation will then flag the mismatch. After the point correspondence is made, the pose is calculated for each identified face.

A direct algorithm determines a unique measurement for the four coplanar points in each face, assuming a perspective vision model. This algorithm first calculates the 3-D coordinates of the points relative to the camera using only the image point locations and the dimensions of the face points from the target model. A rotation matrix and a translation are then found which transform the 3-D target point coordinates in the base or world reference frame to the camera reference frame. Using quaternions to represent this rotation, the best or optimum rotation in a least-square sense that transforms from world to camera coordinates is calculated. The quaternion coordinate system is a method of representing orientation. This system uses four coordinates to specify the orientation in a way that simplifies mathematical operations such as rotation. The translation values are the difference between the centroid of the world points and the centroid of the scaled and rotated camera referenced points.

An error measure is computed from the sum of the distances between the calculated camera-referenced face points and the transformed world target points. This error measure indicates the difference in geometric shape between the derived points and the transformed face points and can be used to indicate an incorrect point assignment as well as a measure quality.

A complete system has been assembled to demonstrate and test the pose calculation method described previously. Figure 1 shows a block diagram of the overall hardware. The major items include a target object, a camera, and an image acquisition and processing computer. The target object and camera are shown in Fig. 2, along with the test fixture. Six infrared light-emitting diodes (LEDs) are arranged at the corners of the front faces on the target.

A commercial camera, the CIDTEC 2250a, is used for viewing the target. It has a 6-mm focal length lens for a wide-angle field of view and an infrared pass filter to block out visible light. The image resolution is 512 by 512 square pixels at 30 frames/s. The camera image is acquired by a Datacube MV200 image processing VME board. This board, along with the main central processing unit, a Motorola MVME167, SCSI disk, and VME chassis, comprise the Datacube MaxTd development system. System software includes the Lynx real-time operating system, Motif X-windows, and Datacube Imageflow™ software. Application software written in C controls the MV200 and programs the processing elements on the board for each pose calculation cycle.

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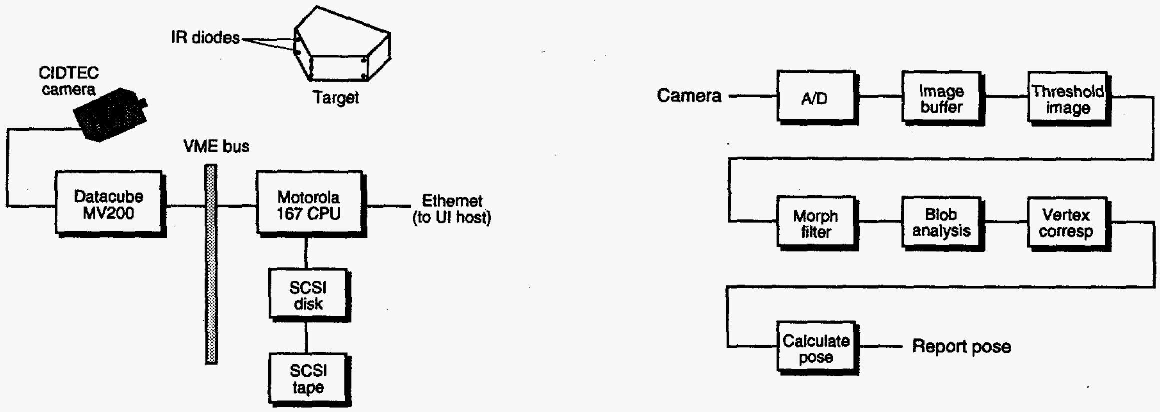

Fig. 1. Block diagram of the prototype vision system to remotely measure the position and orientation of the specified target relative to the camera (left) and functional flow chart of pose determination process (right).

Approximately 100 ms are required to perform the pose calculation. Figure 3 shows the vision system cathode-ray tube screen with the described software program running. One display option that can be selected from the main menu is a live digital image from the camera. This is shown in the photograph as a pattern of LEDs from the target. Overlaying this image are rectangles which outline the LED regions as detected by the program. These regions are identified and connected according to the geometry of the target. The red lines show this connectivity as well as indicate that a valid pose has been calculated. Also shown is the continuous update and display of the calculated pose with translation parameters in millimeters and angles in degrees.

The functional breakdown for the pose determination is shown in Fig. 1. During image acquisition, the MV200 digitizes the camera data to 8 bits per pixel and stores an entire frame in a local memory buffer. At this point the image data corresponding to the LEDs have a greater value than the background illumination. The data are then thresholded to segment the light points and are passed through a morphological filter that removes some artifacts from the image such as single pixel points and small holes within a larger object. Blob analysis is performed next to find the centroid of each LED to subpixel accuracy. Because the LED image is roughly elliptical, filtering is also used at this point to eliminate shapes arising from other sources. The centroid values from the remaining objects are then used to establish point correspondence and connectivity between points from the actual geometry of the 3-D target points.

Two faces are extracted from the six points of the target, and a pose calculation based on the four-point coplanar algorithm is then made from each face. The result giving the lowest error measure is reported as the pose estimate. This pose value is sent to the user interface computer using a command-response protocol based on Unix sockets. Some robustness is built into this implementation in that one light and some patterns of two lights may be obscured without preventing pose determination as long as one face can still be identified.

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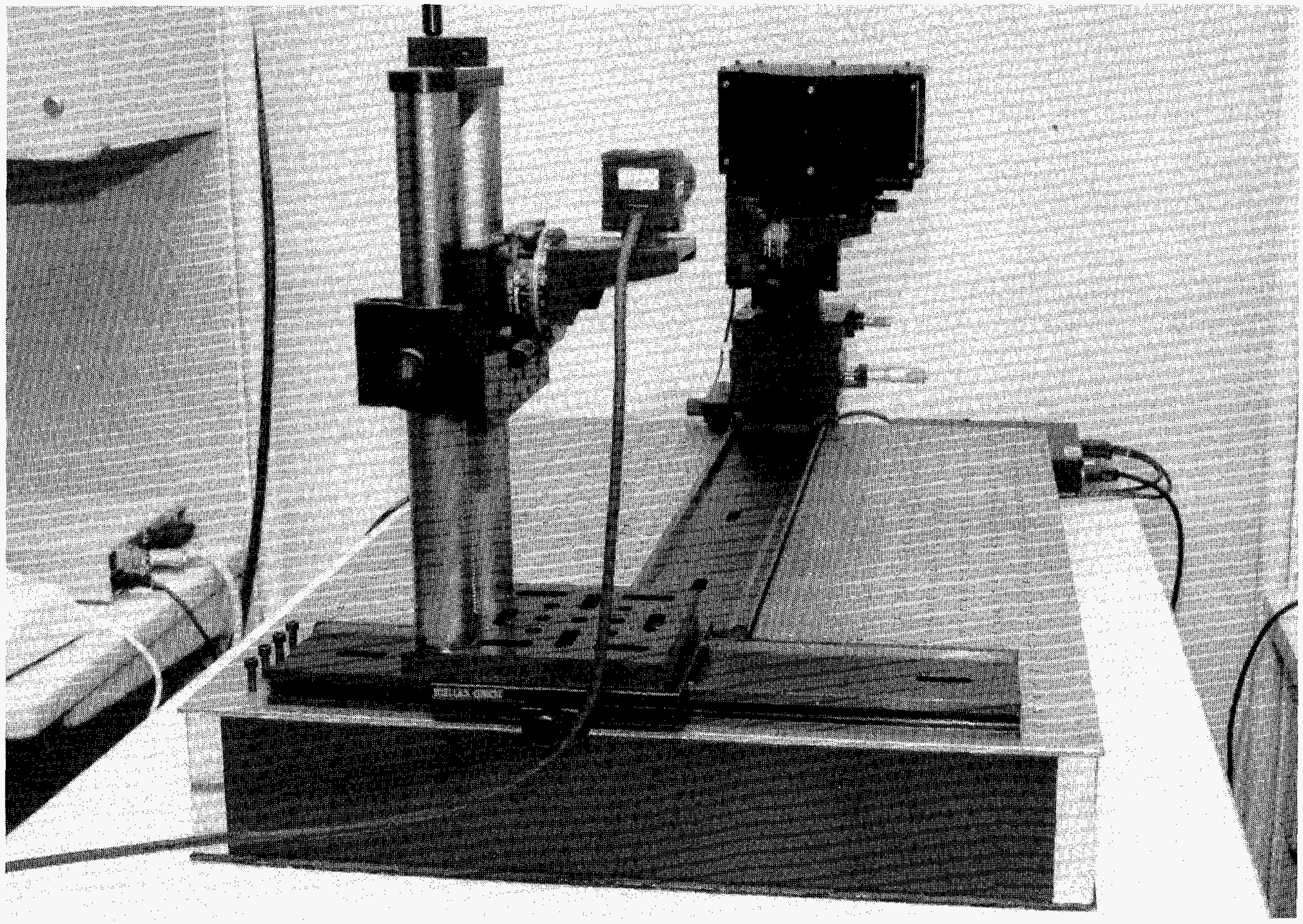

Fig. 2. Target object, camera, and test fixture.

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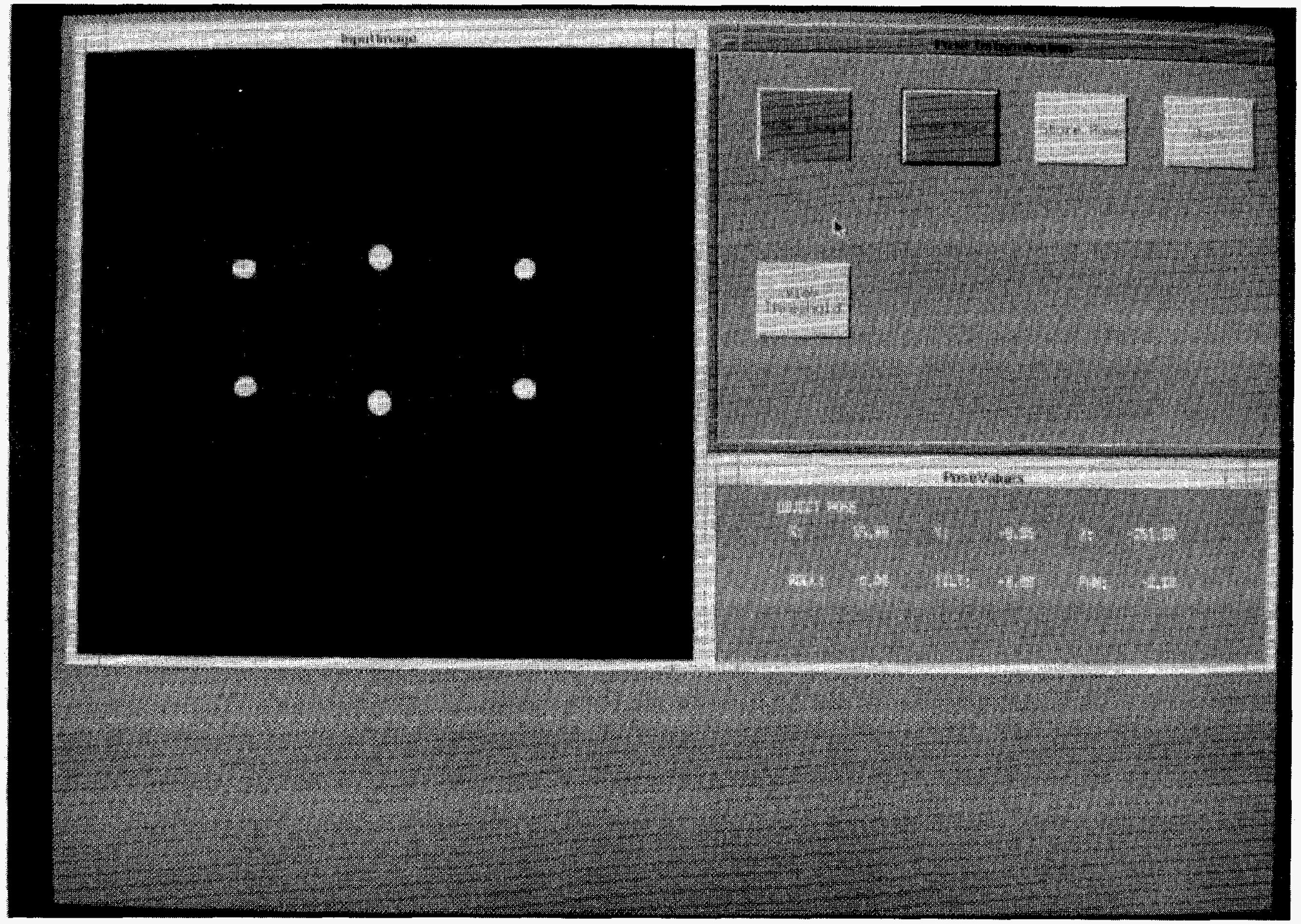

Fig. 3. Vision system cathode-ray tube screen with software program running.

3. CAMERA CALIBRATION

To extract an accurate 3-D position from 2-D image coordinates, the camera's internal geometric and optical characteristics must be known. The parameters required for pose computation are

f = the effective focal length of the camera,

k = the first-order radial lens distortion coefficient,

C_x, C_y = the x and y coordinates of the center of radial lens distortion, and

s_x = the uncertainty factor for scale of the horizontal scan line.

Camera calibration can be defined as the task of computing a camera's intrinsic and extrinsic parameters based on some number of points whose world coordinates (x_w, y_w, z_w) are known and whose image coordinates (x_i, y_i) are measured. To perform the calibration, a specialized target with a large number of precisely spaced points is imaged. Next, the coordinates of the target points in the image must be found to subpixel accuracy. These image coordinates are correlated with the real world position of those target points. This information is then provided to the camera calibration routine, which calculates the camera parameters based on the target data and the camera model.

The calibration target is a grid pattern with horizontal spacing of 1.5 cm and vertical spacing of 1.49 cm. The data points which the calibration routine uses are the subpixel intersections of the horizontal and vertical lines. These data points are located by performing (1) a low-pass filtering operation to emphasize the intersections of the lines and (2) a segmentation to retain only the darkest intensities (blobs about the intersection points). The connectivity and blobs analysis routines supplied by the Datacube Sill Library functions are then used to label the blobs and locate the centroids. These image points are sorted into a logical left-to-right bottom-to-top order to assist in the correlation process. The correlation process involves automatically correlating the image points with a real world coordinate system based on the surface of the target being parallel to the z plane. Once the image points have been correlated with real world coordinate points, these data are provided to the camera calibration program, and the focal length, radial distortion, and the center of the radial distortion are calculated for the camera and lens arrangement.

A well known model for camera calibration was developed by Roger Tsai. His camera calibration routines have been implemented in public domain software and adapted for use in this application. However, his routines utilize an IMSL FORTRAN library routine *dunlsf* for the nonlinear optimization function. Since this library is not in the public domain, *dunlsf* was replaced with a locally available nonlinear optimization routine called *lmdif*. The revised software performed adequately and gave similar results on the sample data set provided with the camera calibration software. An improved version of the calibration software has now been written which improves accuracy for coplanar calibration. After modifying the parameters for the optimization function to more closely match those for our original implementation, the new version has improved performance.

The algorithm requires a perspective view of the target in order to calculate the camera parameters. Therefore, the image plane and the target should not be parallel to each other. An angle of 20 to 30° is preferred between the two objects. The real world origin should not be near the center of the view or near the y axis. However for a coplanar set of points, the target can be considered to be in the $z = 0$ plane. The more points used in the calibration, the less critical the accuracy of the measurement of the real world spacing of the points on the target.

4. GRAPHICAL USER INTERFACE

The graphical user interface (GUI) developed for the simulated docking demonstration is implemented on a Sun SPARCstation 10/30 using X-windows (X11R5) protocol and Motif (Version 3.0) widgets. Several different techniques for graphically representing the pose information of the docking port are being implemented on the dashboard simulation GUI. In autonomous docking modes, the GUI display is used by the operator to monitor the path of the robotic arm. For manual docking modes, the GUI is intended to improve the operator's ability by providing a supplementary viewpoint. The challenge in this development is to provide an operator with information about 6 D.F. on a 2-D screen. The current version of the GUI is described in the following paragraphs.

One way to show all 6 D.F. on the screen is to implement position instruments and text displays as shown in Figs. 4 and 5. The sliders in Fig. 4 are used to show the position (x, y, z) of the port in 3-D space. A text readout above the slider handle displays the corresponding position in inches relative to the center of the port.

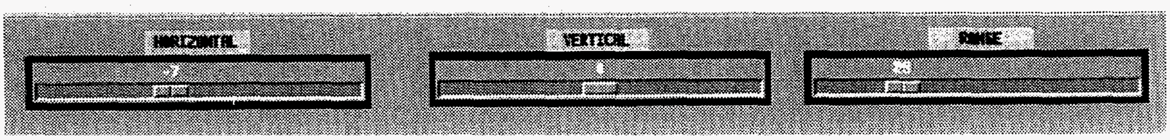

Fig. 4. Sliders.

The position of the needles in the gauges shown in Fig. 5 provides orientation information about the docking port. There is also a text display at the center of each gauge that presents to the operator numerical orientation values in degrees. Although the gauges and sliders provide all of

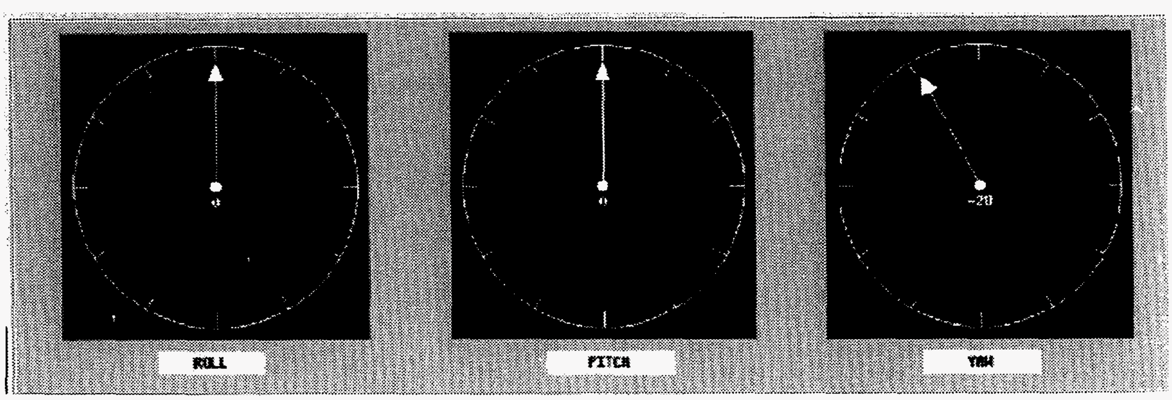

Fig. 5. Gauges.

the necessary pose information, an operator would have a difficult time aligning with the port using sliders and gauges alone because it is not possible to watch all of the readouts at the same time. More importantly, gauges, sliders, and numbers do not provide an intuitive feel for the actual position of the robotic arm relative to the port. For this reason a simulated viewport was developed which contains an image of an AFAS vehicle with a port and visual aids that indicate pose information.

For this implementation of the GUI, a fixed image of the docking port was used as a backdrop for the graphical pose indicators, as shown in Fig. 6. The complete GUI display screen is shown in Fig. 7. For future implementations, a high-performance graphics workstation will be used to render and animate 3-D models of the AFAS for more realistic docking simulations. The image of the port and the associated pose widget shown in Fig. 6 has each component labelled with its intended function. Each component is described in the following sections.

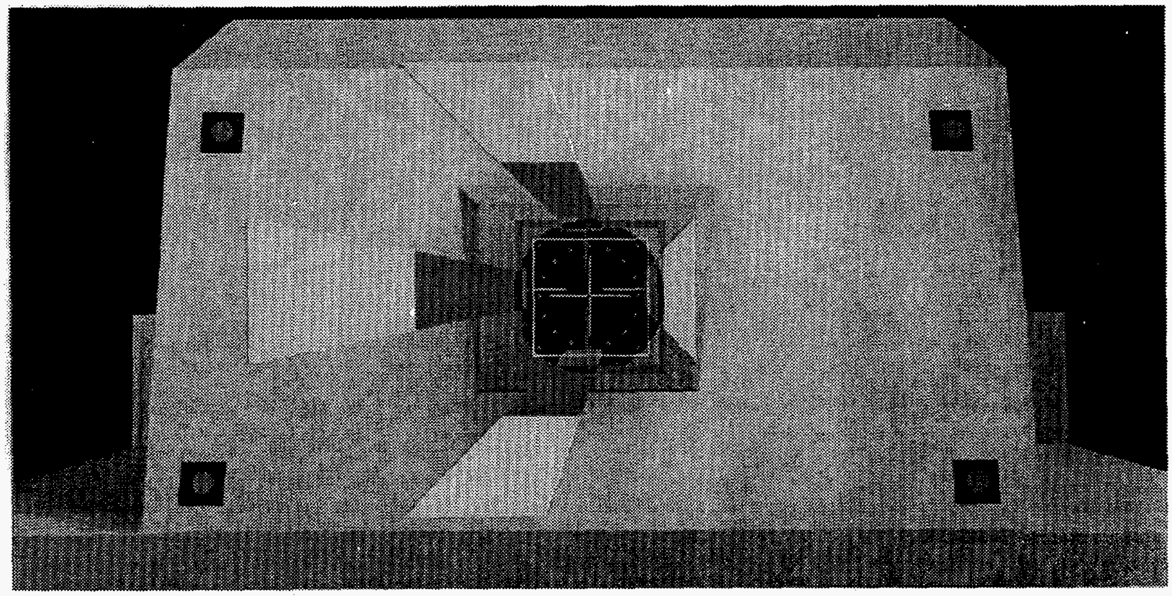

Fig. 6. Graphical pose indicators.

4.1 X-Y TARGET CROSSHAIR

The X-Y target crosshair is a fixed crosshair on the center of the docking port that serves as a target for proper X-Y positioning.

4.2 X-Y ALIGNMENT CROSSHAIR

The X-Y alignment crosshair moves with the position of the camera. When it is aligned with the X-Y target crosshair, then the line of sight (LOS) of the camera is directly at the center of the port. In Fig. 6 the camera LOS is closely aligned with the center of the port.

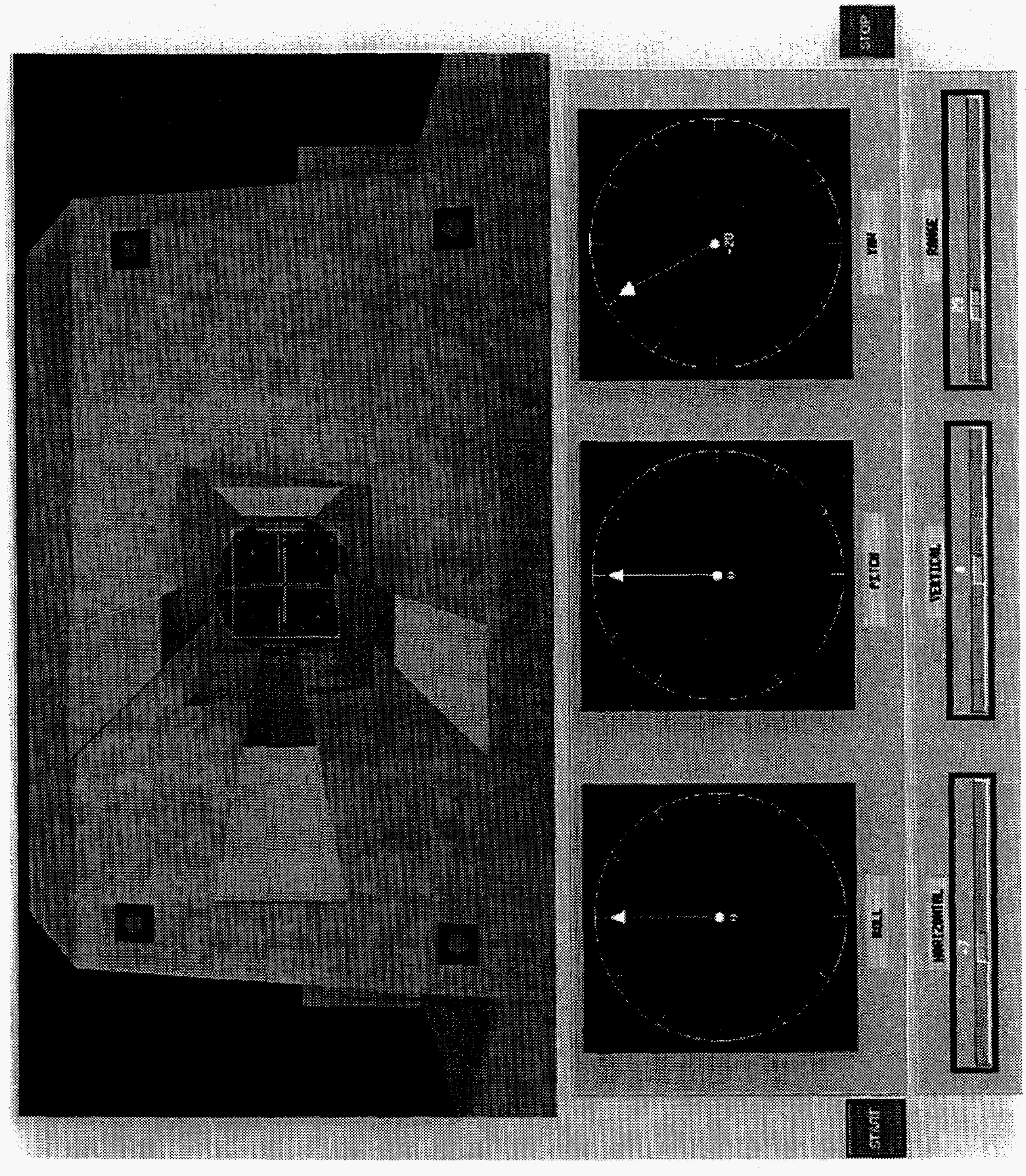

Fig. 7. GUI display screen.

4.3 LOS INDICATORS

LOS indicators are the four arms of the pose-indication widget that provide information on the roll, pitch, and yaw of the arm relative to the port. The four arms can be compared to the interior of a tunnel that indicates the LOS path from the camera on the robotic arm to the center of its field of view. In Fig. 6 the LOS indicators are skewed to the left, indicating a significant positive yaw orientation. Note how the left arm is much wider than the right arm and how the top and bottom portions of the crosshair start near the center of the port but then extend out to the left as they project outward to the operator. This should indicate to the operator that the robot arm is to the left of the port and that the camera is looking toward the center of the port. The pitch vector is approximately normal to the port, indicated by the lack of skew in the positive or negative y-direction. Variations in the roll orientation are indicated by the rotation of the entire widget (including the X-Y alignment crosshair) about its center. The roll value indicated in Fig. 6 is zero.

4.4 COLOR TRANSITION RANGE INDICATORS

On a color display, the outer portions of the LOS are red while the inner portions are green. The color transition range indicators are located at the red-to-green transition in each of the four LOS indicators. As the camera gets closer to the port, the color transition moves in toward the center of the LOS indicator, resulting in more of the indicator becoming red. As the camera moves further away from the port, the color transition border moves out toward the ends of the LOS indicator, resulting in more of the indicator becoming green.

4.5 TARGET RANGE BOX

This fixed-position green box indicates the desired range value for docking. When the four-color transition range indicators overlay the target range box, the robotic arm is the proper distance from the port for docking.

5. CONCLUSIONS

A complete error analysis at various positions and orientations using the test setup is ongoing. Preliminary results show that this system can provide reliable measurements of the target object with respect to the camera from 6 in. away to about 7 ft away. These distances are strongly dependent on the focal length of the lens used and the brightness of the LEDs and do not reflect the limits of this method. Relative position errors have been found to be less than 1%.

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