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A SPACE SERVICING TELEROBOTICS TECHNOLOGY DEMONSTRATION

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Introduction

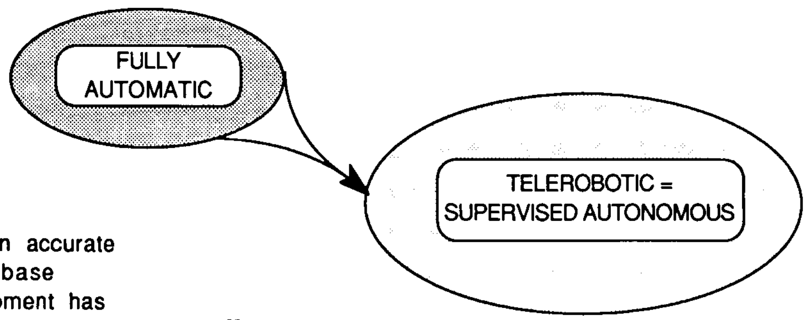
SUPERVISED TELEROBOTIC CONTROLS PROVIDE THE KEY TO SUCCESSFUL REMOTE SERVICING, AS DEMONSTRATED IN THE TELEROBOT TESTBED OF THE JET PROPULSION LABORATORY. SUCH ADVANCED TECHNIQUES AND SYSTEMS ARE SPECIALLY APPLICABLE TO GROUND-REMOTE OPERATIONS FOR SERVICING TASKS, WHICH ARE TO BE PERFORMED REMOTELY IN SPACE AND TO BE OPERATED UNDER HUMAN SUPERVISION FROM THE GROUND. LABORATORY DEMONSTRATIONS HAVE SUCCESSFULLY PROVEN THE UTILITY OF SUCH TECHNIQUES AND SYSTEMS.

INSTRUMENTAL TO THE SUCCESS OF SUPERVISED ROBOTIC OPERATIONS ARE THE TECHNIQUES CALLED **"OBJECT DESIGNATE"** AND **"RELATIVE TARGET"**. IN ADDITION, A TECHNIQUE CALLED "UNIVERSAL CAMERA CALIBRATION" WAS ALSO APPLIED IN THE TELEROBOT TESTBED. "GENERALIZED COMPLIANT CONTROL" TECHNIQES WERE USED IN THE ROBOTIC REMOVAL AND INSERTION OPERATIONS.

THESE TECHNIQUES WERE PROVEN SUCCESSFUL IN TASK SITUATIONS WHERE PREPROGRAMMED AUTOMATION CANNOT BE ADEQUATELY EXERCISED DUE TO ERRORS, CHANGES, OMISSIONS ETC., IN THE WORKSITE DATA BASE.

Progressive Technology for Robotic Satellite Assembly and Servicing

EARLIER DESIGN APPROACH ——▸|◂—— PRESENT RESEARCH TREND



- o Rely on accurate data base
- o Envirnoment has to be structured
- o Computer vision technique has limited performance

- o Tolerate error in data base; use 'relative target' technique
- o Can handle less structured environment
- o 'Object designate' technique uses full capability of human vision

- o Handle time delay, as in ground-remote operations
- o Expanded set of servicing demonstrations
- o Integrated system

Description of the Techniques
The Robot System & Environment

THE TASK: THE ROBOT MANIPULATOR IS TO BE COMMANDED TO

- o REMOVE THE EXISTING ORU (ORBIT REPLACEABLE UNIT) FROM ITS INSTRUMENT RACK;
- o INSERT THE ORU INTO A HOLDING RACK; and
- o FETCH A NEW ORU (SPARE), AND INSTALL IT IN THE INSTRUMENT RACK.

INFORMATION AND RESOURCES AVAILABLE:

- o DATA BASE OF WORKSITE - NOMINAL LOCATION (AND ORIENTATION) OF THE WORK SITE IS KNOWN. HOWEVER, THE ACCURACY IS CURRENTLY IMPAIRED BEYOND THE 5- 10 mm CHAMFER ACCURACY; i.e. PREPROGRAMMED AUTOMATION WILL NOT SUCCEED, GIVEN THIS ACCURACY. PRESENT TECHNIQUES APPLY EVEN IF THE DATA BASE WERE ABSENT.
- o DIMENSIONS (AND MODELS) OF ORU AND ROBOT GRIPPER ARE KNOWN TO BLUE-PRINT ACCURACY (DIGITIZED TO 1 mm ACCURACY).
- o TWO CAMERAS, MONITORS AND ASSOCIATED GRAPHICS ELECTRONICS ARE USED FOR THE PHOTOGRAMMETRIC LOCATION OF OBJECTS. COMMERCIAL GRADES ARE USED.
- o MODELS OF THE CAMERAS ARE KNOWN. PHOTOGRAMMETRIC ACCURACIES REQUIRED TO BE OF THE ORDER OF 10 cm.

Telerobotics for Space Servicing (cont.)

NEW TECHNOLOGY USED

- o "OBJECT DESIGNATE" TECHNIQUE - AN OPERATOR INTERACTIVE TECHNIQUE TO UPDATE TELEROBOT DATA BASE, SPECIFICALLY OBJECT LOCATION/ORIENTATION
- o "RELATIVE TARGET" TECHNIQUE - AN ALGORITHMIC APPROACH TO COMPUTE THE RELATIVE TARGETING VECTOR, USING DATA OBTAINED FROM THE SAME CAMERA VIEW OF THE ROBOT PRESENT LOCATION AND THE DESIRED ROBOT DESTINATION.
- o "UNIVERSAL CAMERA CALIBRATION" MODEL - AN ALGORITHM TO DETERMINE CAMERA MODEL FOR ANY LOCATION IN ITS WORKSPACE, GIVEN ONLY ONE ABSOLUTE CALIBRATED MODEL AT ONE PREDETERMINED LOCATION.
- o "GENERALIZED COMPLIANT CONTROL" TECHNIQUE - AN ADVANCED CONTROL TECHNIQUE PACKAGED TOGETHER, FOR EASY ON-LINE SEQUENCING OF CONTROL ACTIONS REQUIRED OF ROBOTIC SERVICING.
- o "GUARDED MOVE" AND "MOVE-TO-TOUCH" TECHNIQUE - ADVANCED CONTROL PRIMITIVES, USED IN CONJUNCTION WITH THE COMPLIANT CONTROL PRIMITIVE.

"Object Designate" Technique -

PURPOSE: TO DETERMINE THE LOCATION (AND ORIENTATION) OF AN OBJECT IN THE WORKSPACE, WHEN THE DATA BASE ON THIS OBJECT IS INACCURATE OR ABSENT.

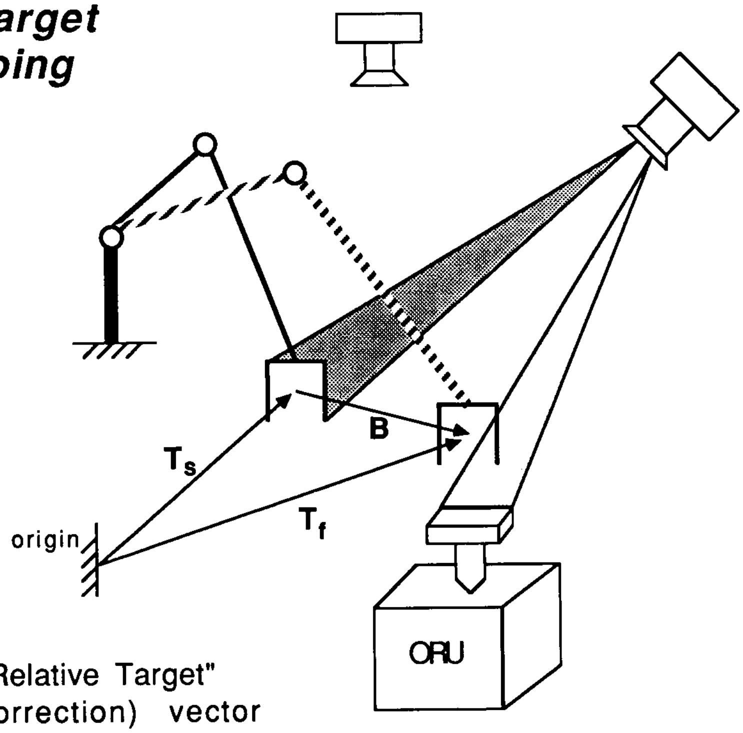
HOW IT IS PERFORMED: VIA A HUMAN-MACHINE INTERACTIVE GRAPHIC OVERLAY PROCESS, USING THE MOUSE TO DESIGNATE AND CLIKE POINTS ON VIDEO MONITORS, THE OPERATOR:

i. LOCATES THE OBJECT IN A TWO VIDEO IMAGES;
ii. DESIGNATES SEVERAL VERTICES OF THE OBJECT IN THE VIDEO IMAGES;
iii. ASSOCIATES THESE VERTICES TO THE OBJECT MODEL, AS OVERLAID ON THE VIDEO;
iv. EVALUATE THE GOODNESS OF FIT; COMPUTE AND UPDATE OBJECT DATA BASE.

RESULTS OF OBJECT DESIGNATE PROCESS: THE OBJECT DATA BASE IS THEN UPDATED (if previous readings are inaccurate), OR GENERATED (if it is absent to start with); TO THE ACCURACY PERMITTED BY THIS GRAPHICS AND HUMAN VISION PROCESS. ACCURACIES EASILY ATTAINABLE WITH COMMERCIAL PRODUCTS ARE REQUIRED TO BE WITHIN 10 cm.

IF OBJECT DESIGNATE PROVIDES ACCURACY OF WITHIN 5-10 mm., AUTOMATIC ROBOT ACTIONS CAN PROCEED. SUCH ACCURACY IS ACHIEVABLE WITH CALIBRATED CAMERA MODELS. OTHERWISE, USE RELATIVE TARGET TECHNIQUE.

Relative Target robot servoing technique



B = "Relative Target" (correction) vector

"Relative Target" Technique

<u>PURPOSE:</u> TO FIND THE RELATIVE, I.E. CORRECTION VECTOR, SO THAT THE ROBOT WILL BE DIRECTED FROM ITS APPROACH POINT TO ITS DESTINATION TARGET POINT; ACCURACY ATTAINED AT THE TARGET POINT WILL BE WITHIN 5-10 mm, i.e. WITHIN CHAMFER TOLERANCES. THIS TECHNIQUE EMPHASIZES ON A RELATIVE VECTOR, INSTEAD OF AN ABSOLUTE VECTOR.

<u>HOW IT IS PERFORMED</u>: THIS RELATIVE TARGET PROCESS IS OPERATED IN CONJUNCTION WITH THE OBJECT DESIGNATE PROCESS:

i. OBJECT DESIGNATE THE APPROACH POINT, i.e. present robot gripper location;
ii. OBJECT DESIGNATE THE TARGET POINT, i.e. ORU grapple lug location (minus a safe approach vector);
iii. COMPUTE RELATIVE VECTOR (a software process);
iv. SEND RELATIVE VECTOR TO ROBOT CONTROLLER FOR SUBSEQUENT MOTION.

<u>RESULTS OF RELATIVE TARGET PROCESS:</u> ROBOT WILL BE DIRECTED ACCURATELY TO TARGET POINT, BEYOND WHICH AUTOMATIC ORU REMOVAL/INSERTION ACTIONS CAN BE COMMANDED. ACCURACIES ACHIEVED ARE WITHIN 5-10 mm. (COMPLIANT ROBOT MOTIONS ARE NORMALLY EXERCISED.)

Generalized Compliant Motion Primitive

PURPOSE: PROVIDE THE SPECIFICATION OF ROBOT MOTION EXECUTION COMMAND VIA PARAMETRIZATION. PROVIDE A SIMPLE, LOW BANDWIDTH, AND UNIFIED INTERFACE BETWEEN THE PLANNER AND THE ROBOT CONTROLLER. (PLANNER CAN BE AN ARTIFICIAL INTELLIGENCE PLANNER OF SIMPLY THE HUMAN OPERATOR.)

THE GENERALIZED COMPLIANT MOTION PRIMITIVES, ALSO KNOWN AS MOTION MACROS, UNIFY THE SPECIFICATION OF MOTIONS SUCH AS (i) FORCE-POSITION COMPLIANT CONTROL; (ii) GUARDED MOTION; AND (iii) MOVE-TO-TOUCH ROBOT MOTIONS. ALL FORSEEABLE MOTIONS TYPICAL IN A ROBOT OPERATION SCENARIO CAN BE SPECIFIED BY THIS GENERALIZED PRIMITIVE/MACRO, INCLUDING THE FOLLOWING:

- PIN INSERTION / REMOVAL
- DOOR OPENING
- CRANK TURNING
- CONTOUR FOLLOWING
- PUSHING
- SLIDING
- LEVELING GRIPPERS ON GRAPPLE LUGS
- etc.

ORU Removal Sequence

STEP 1 STAGE ROBOT GRIPPER TO VICINITY (e.g. 25 cm above) OF THE ORU GRAPPLE LUG.

STEP 2 EXAMINE WHETHER GRIPPER APPEARS TO BE ABOVE ORU GRAPPLE LUG.
- (i) IF YES, MOVE GRIPPER TO FINAL APPROACH POINT (5 cm above), AND PROCEED TO STEP 6.
- (ii) IF NO, GO TO STEP 3.

STEP 3 INITIATE 'OBJECT DESIGNATE' OPERATION OF ROBOT GRIPPER
- (a) ACQUIRE CAMERA ARM POINTING POSITION
- (b) COMPUTE CURRENT CAMERA 'cahv' MODEL PARAMETERS
- (c) SEND GRIPPER MODEL AND CAMERA MODEL TO OCS
- (d) PERFORM MULTI-POINT 2-VIEW DESIGNATION
- (e) PERFORM LEAST SQUARES FIT TO OBTAIN GRIPPER T6
- (f) TRANSMIT NEW GRIPPER T6 TO 'RELATIVE TARGET' PROCESS

STEP 4 REPEAT STEP 3 FOR ORU GRAPPLE LUG

STEP 5 COMPUTE 'RELATIVE TARGET' VECTOR FOR GRIPPER FINAL APPROACH POINT (5 cm above grapple lug)

STEP 6 EXAMINE VECTOR. IF OK, PROCEED; OTHERWISE GO BACK TO STEP 3.

(to be continued)

ORU Removal Sequence (cont.)

STEP 7 INITIATE MOVE_TO_TOUCH COMPLIANT CONTROL PRIMITIVE. (Use this primitive with the appropriate parameters, including gripper model, payload model, maximum safe travel distance, encounter force/torque, backoff force/torque, coordinate systems, robot specifications etc. In demo, this is mtouch_tri_z100_r macro-primitive.)

STEP 8 IF SUCCESSFUL, PROCEED; OTHERWISE ABORT, OR GO BACK TO STEP 3

STEP 9 INITIATE COMPLIANT_GRASP COMPLIANT CONTROL PRIMITIVE. (Use this primitive with the appropriate parameters, including maximum push force, safety limits, application coordinate systems, gripper close command etc. In demo, this is grasp_close_fz10_r macro primitive.)

STEP 10 IF SUCCESSFUL, PROCEED; OTHERWISE ABORT, OR GO BACK TO STEP 3.

STEP 11 INITIATE COMPLIANT_REMOVE COMPLIANT CONTROL PRIMITIVE TO REMOVE ORU. (Use this primitive with the appropriate parameters, including distance to be traveled, maximum force/torque limits, tool frames etc. In demo, this is remove_electr_mainNegx_r macro primitive.)

STEP 12 IF SUCCESSFUL, TASK IS DONE; OTHERWISE ABORT OR REPEAT WITH DIFFERENT PARAMETERS.

Conclusion

DEMONSTRATED MERITS OF THIS TELEROBOTIC APPROACH

- o *TOLERANCE* TO LESS STRUCTURED ENVIRONMENT - INCORRECT DATA BASE CAN BE INTERACTIVELY UPDATED BY THE "OBJECT DESIGNATE" TECHNIQUE
- o *ROBUST* DESIGN - DEGRADATION OF ROBOT ARM MODELING PARAMETERS CAN BE TOLERATED, USING THE "RELATIVE TARGET" TECHNIQUE
- o *ROBUST* DESIGN - ABSOLUTE CAMERA CALIBRATION OVER THE ENTIRE VOLUME IS NO LONGER NECESSARY; ONLY ONE SET OF CALIBRATED DATA (AT ANY ONE POINT IN THE WORK VOLUME) IS REQUIRED.
- o *FLEXIBILITY* - USING THE GENERALIZED ROBOT COMMAND MACROS, A COMMAND SEQUENCE CAN BE EASILY TAILORED TO EACH SERVICING SCENERIO
- o *SUPERVISED AUTONOMY* - THIS CAN OVERCOME CONTROL BARRIERS SUCH AS THOSE FROM TIME DELAYS
- o SUITABLE FOR *GROUND-REMOTE OPERATIONS* - THIS APPROACH IS BEST SUITED FOR GROUND-REMOTE and/or STATION-REMOTE OPERATIONS.

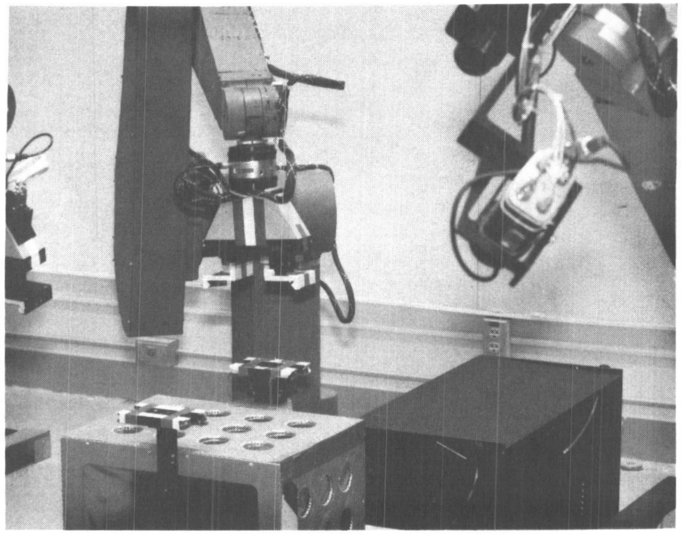


Figure 1 ROBOT WORKSITE AT THE JPL TELEROBOT TESTBED - ROBOT ARM STAGED OVER ORU; CAMERAS ON CAMERA ARM

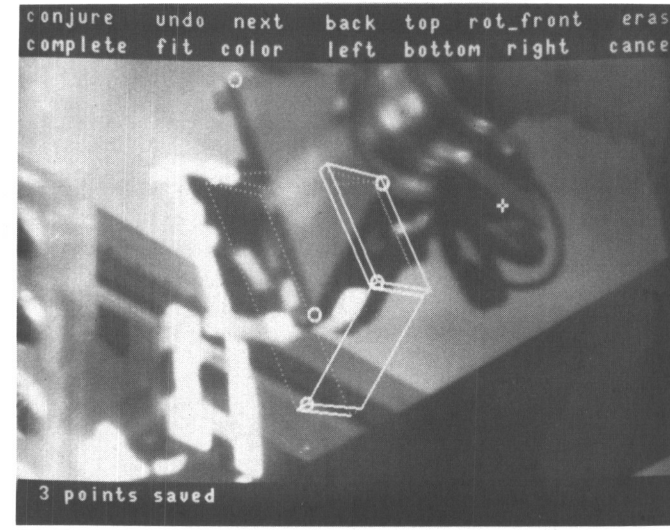


FIGURE 2 "OBJECT DESIGNATE" ROBOT GRIPPER - WIRE FRAME MODEL OVERLAID ON VIDEO; RIGHT CAMERA VIEW

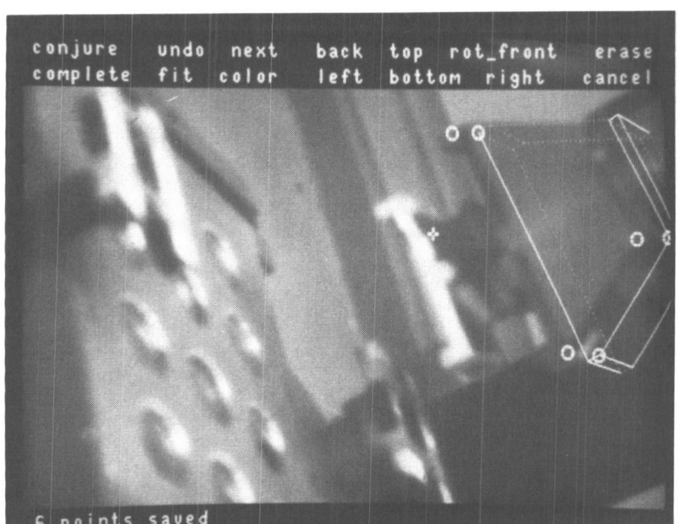


FIGURE 3 "OBJECT DESIGNATE" ROBOT GRIPPER - WIRE FRAME MODEL OVERLAID ON VIDEO; LEFT CAMERA VIEW

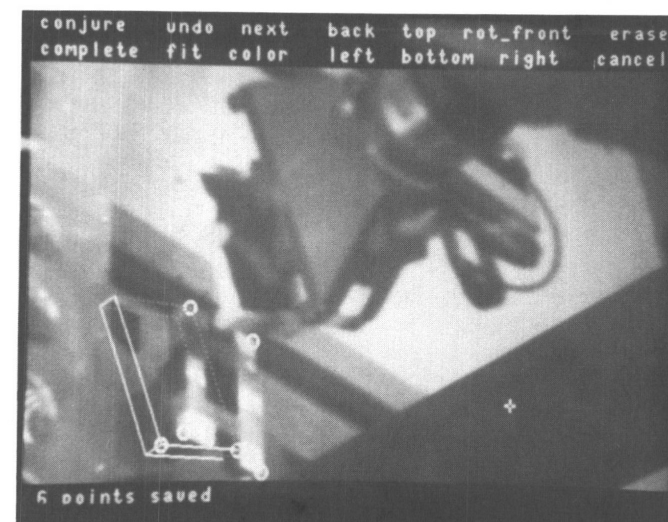


FIGURE 4 "OBJECT DESIGNATE" ORU GRAPPLE LUG - WIRE FRAME MODEL OVERLAID ON VIDEO, RIGHT CAMERA VIEW

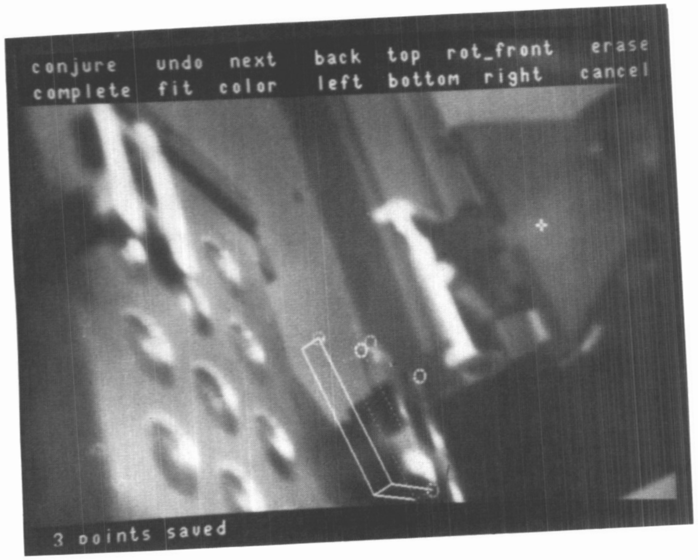


Figure 5 "OBJECT DESIGNATE" ROBOT GRIPPER - WIRE FRAME MODEL OVERLAID ON VIDEO; LEFT CAMERA VIEW

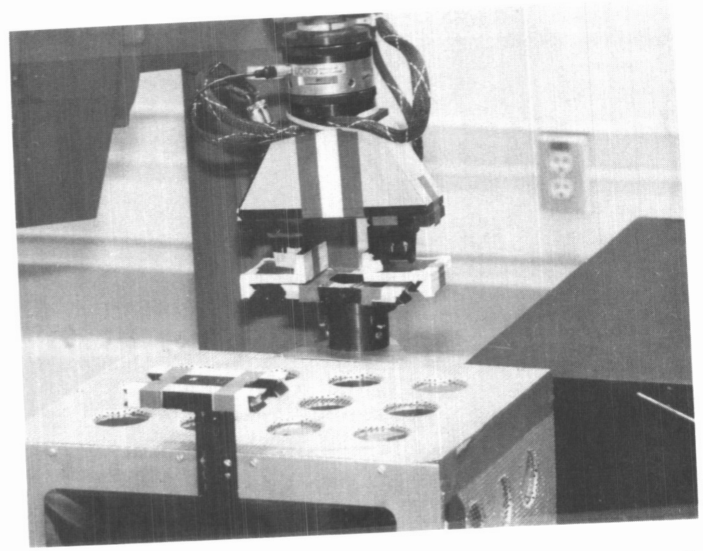


FIGURE 6 "RELATIVE TARGET" VECTORING OF ROBOT GRIPPER TO ORU, THEN "MOVE_TO_TOUCH" COMMANDING OF ROBOT

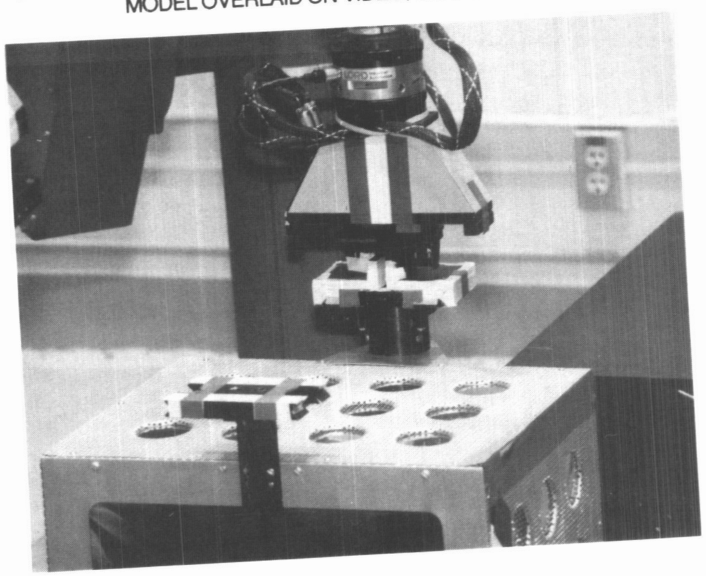


FIGURE 7 RESULT OF "COMPLIANT_GRASP" COMMAND - A GENERALIZED COMPLIANT CONTROL MACRO COMMAND

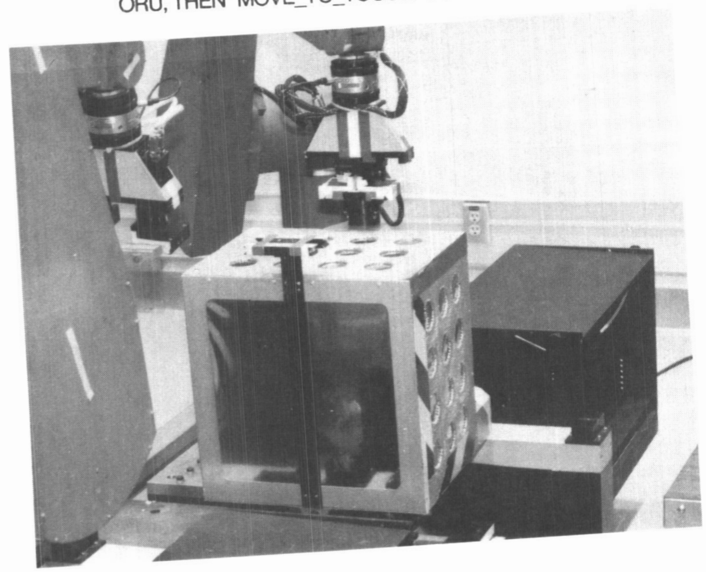


FIGURE 8 RESULT OF "COMPLIANT_ORU_REMOVE" COMMAND - A GENERALIZED COMPLIANT CONTROL MACRO COMMAND