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FORCE/TORQUE DISPLAY FOR SPACE TELEOPERATION CONTROL EXPERIMENTS AND EVALUATION

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ABSTRACT

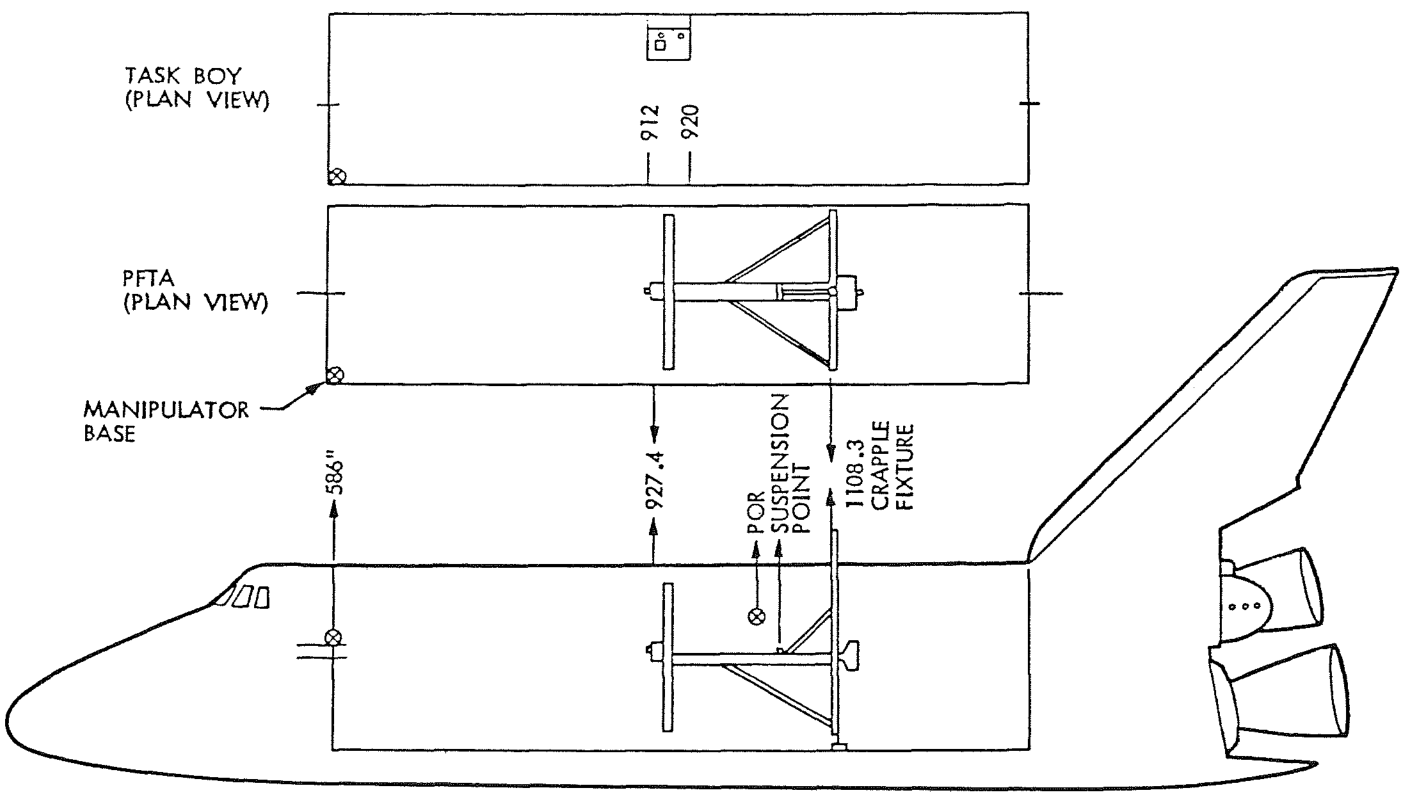
Experiments were performed at the Johnson Space Center (JSC), Manipulator Development Facility using the full scale Shuttle Remote Manipulator System (SRMS) to evaluate the effect of visual presentation through perspective display of the orthogonal forces and torques sensed at the manipulator end effector. The experiments investigated the effect of the display information on the management of forces and torques generated during payload berthing and deployment, as well as simulated satellite module change-out operations. The evaluation also addressed (i) issues of display format, including: force/torque scaling, point of resolution, and display mixing with video generated imagery, and (ii) task related variables of payload size, alternative sources of guidance information, and control mode.

This paper briefly presents the results of a first-pass informal analysis of the analog, strip chart-recorded data from these evaluation tests. The results provide a relative measure of improvement in force management through the use of such a display, as well as information regarding the impact of display variables and task demands on operator performance.

1.0 INTRODUCTION

Two experiments were performed at the JSC Manipulator Development Facility using the full-scale Shuttle RMS and the JPL two hundred pound range force/torque (F/T) sensor, four-claw end effector, and a perspective visual display of the forces and torques sensed at the end-effector. The equipment used in these tests, with the exception of the perspective display system, are described in a previous evaluation report by Bejczy and co-workers (1982).

The two evaluation sessions provided an assessment of the effect of the F/T sensor and display system on SRMS performance. The first session investigated operator handling in large payload berthing. The second session dealt with small tool handling and simulated module change-out performance. Figure 1 provides a plan view of the payloads, their size, and location for the tests, in relation to the Rockwell



PAYLOAD LOCATIONS IN JSC MDF
FORCE/TORQUE DISPLAY

Figure 1.

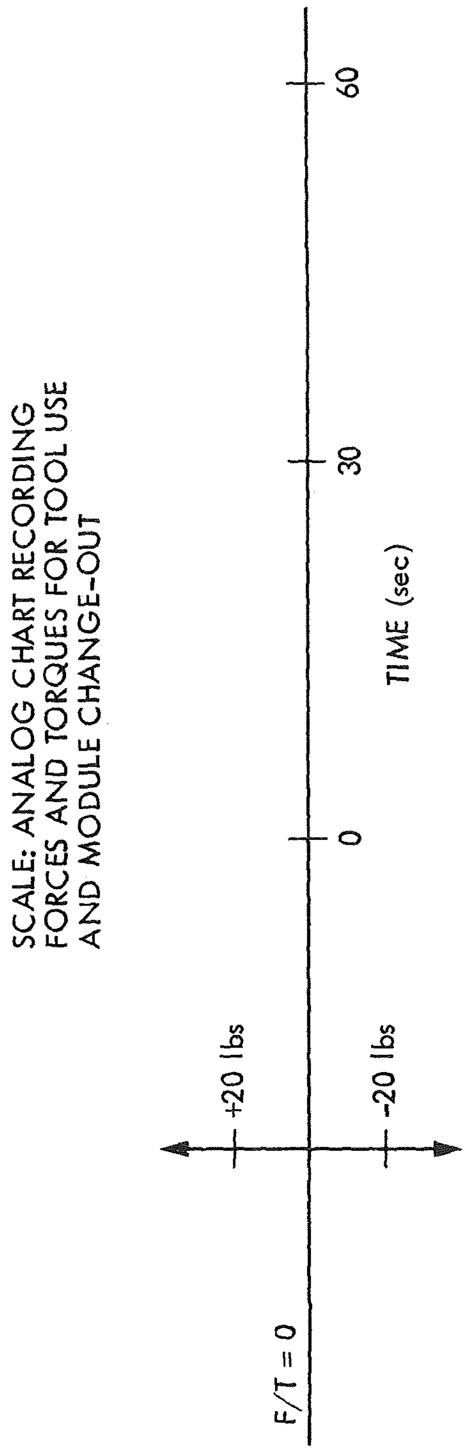

SCALE: ANALOG CHART RECORDING
FORCES AND TORQUES FOR TOOL USE
AND MODULE CHANGE-OUT
F/T = 0
+20 lbs
-20 lbs
0
30
60
TIME (sec)

Figure 1b.

Shuttle point of reference (POR), i.e., 236 in. forward of and 400 in. below the orbiter nose point.

The evaluation tasks were performed by four JSC personnel who were trained and MDF qualified in the use of the shuttle RMS simulator. The tests were performed in two sessions each of one week duration and separated by a six month hiatus.

1.1 Display Characteristics

The characteristics of the display format used for these evaluation are presented here. Since the time of these tests, we have made substantial progess in creating a three dimensional perspective display. This display technique is described in the final section of this paper on future research efforts.

(i) The display, pictured in Figure Two, presents force and torque as filling from the center of the six axis perspective frame. The point of reference for the axes can be manipulated in software to correspond to the control reference frame of the operator, or any other reference frame deemed appropriate to the task. In the case of the PFTA payload, the X axis relates to the fore/aft axis of the orbiter, the Z axis refers to the elevation in and out of the payload bay, and the Y axis designates port/starboard across the payload bay. The torques about these axes are designated by filling of the pitch, roll, and yaw frames associated with each of the torques. In the case of the tool handling and module change out procedures, the display is referenced to the end effector and sensor reference frame as illustrated in Figure 3b.

(ii) The display provides force and torque readings to the operator referenced to the point of resolution (POR) of the PFTA payload, in the first evaluation, and referenced to the sensor reference frame in the second evaluation. (The POR can be varied through software manipulation of the data provided by the sensor system and can be calculated for the desired operator perspective, dependent on payload geometry.) The POR chosen for the large payload berthing was the center of geometry of the payload. This POR is forward of the center of mass of the payload to compensate for the small residual frictional forces associated with the payload counterweight system. The MDF counterweight system serves to simulate zero gravity operation for high mass payloads, such as the PFTA.

(iii) The "sense" of the displayed forces shows the effect of the operator's control input on the payload. For example, in the case of PFTA manipulation, a roll to port that generates contact forces with the \port trunions is displayed as an increased torque to port and an increased Z force. The corrective control action to reduce these forces and torques is to roll starboard, i.e., the operator acts as if to push the extending display bar to zero, the center point. Operators generally found this "fly to" arrangement intuitive. However, when the payload is viewed from the aft cameras the sense of the display in terms of required corrective action is reversed. This caused some confusion,

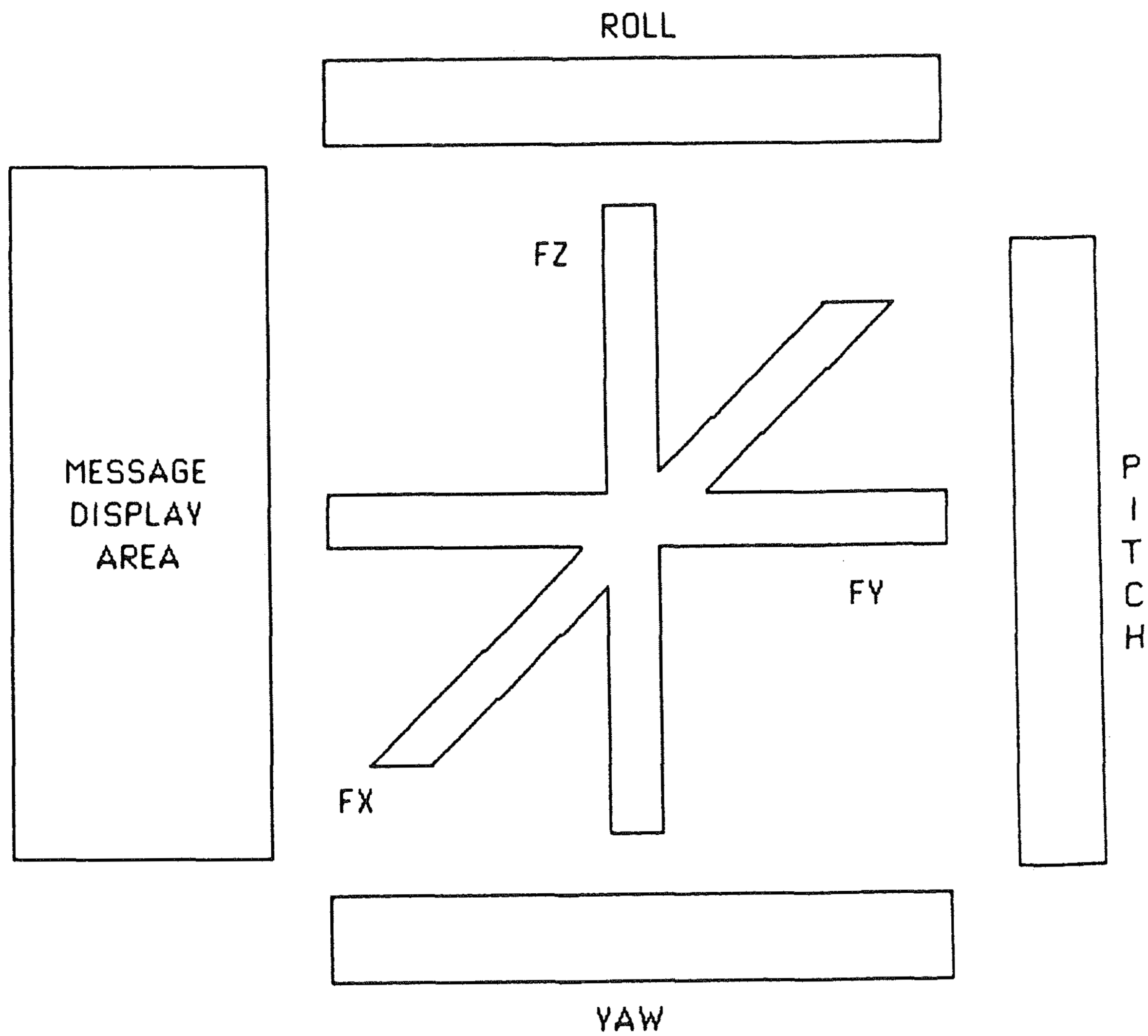


Figure 2. Display Format

and argues for a display reference that is dynamically referenced to the point of regard of the operator. Experiments and software requirements for such transformations are currently under consideration by the authors.

(iv) Force/Torque display scaling proved sensitive to the payload geometry. Because of the large moment arm of the PFTA payload, torques generated at the bay trunions saturated the torque scaling more quickly than forces about the POR. Software decoupling and rescaling of the torque display was accomplished, but there is some danger in this approach, in that sensor saturation may not bear a clear relation to display saturation. Future work will seek to provide both sensor and display saturation scales to the operator.

(v) The display size could be reduced to allow split screen mixing with an operator selected camera view of the payload.

1.2 Performance Data

The data collected were (i) total task time, defined as operator control initiation to payload berthed and latched condition, (ii) analog chart recording of the forces and torques sensed about three orthogonal force and three orthogonal torque axes of the sensor POR during the berthing operation, and (iii) digital recording of these forces and torques. In this preliminary evalution, statistical analysis is precluded by the large number of treatment conditions in relation to the number of data points gathered in the analysis. The evaluation was designed to survey the relative impact of the provision of and the format of visual F/T feedback, rather than to establish statistically robust parameterization of that effect.

2.0 EVALUATION PROTOCOL

2.1 Large Payload (PFTA) Berthing

Task:

The performance required for this evaluation involved berthing the PFTA payload after it was deployed to a random position above the paylad bay trunion guides. The task represents the precision placement portion of a payload berthing task. The berthing task was performed ten times by each subject after familiarization and briefing runs on the display characteristics. The ten test trials were performed under varied feedback and control conditions as illustrated in Table I. The control point of reference for these tests was the orbiter control mode, in which the operator controls the end effector of the RMS in relation to the shuttle body. Translation axes of the two-handed controller refer to for/aft, port/starboard, and elevation in/out of the bay. Rotational axes of pitch, roll and yaw are referenced to these trannslational axes. (The control mode for the majority of the tests was a resolved rate control. The exception to this was a joint by joint control mode which had its greatest impact in dramatically increasing required performance

Trial	Camera				Display		Control Mode	
	Port Aft	Starbrd Forward	Starbrd Aft	Elbow	Digital	F/T	Orbiter Loaded	Single Joint
1	*	*	*	*	*	*	*	
2	*		*		*	*	*	
3		*		*	*	s/s	*	
4	*				*		*	
5	*	*	*		*		*	
6						*	*	
7	*	*	*		*			*
8		*			*	*		*
9				*	*	*	*	
10	*					*		*

* Indicates sensor available or mode used.

S/S = Split Screen

Table 1. Feedback and Control Conditions
for PFTA Berthing Experiments

time for all operations.)

Results:

A very general discussion of results is presented for this task. Analysis of the digital data, as opposed to the analog chart recording, is being pursued with the intent to describe the effect of the varied feedback views in conjunction with the F/T display. At this point we will confine our discussion to the management of forces and torques with and without the visual display from the sensor.

(i) Force/Torque generation:

- Provision of force/torque information via the visual display reduced the loads on the PFTA payloads and payload guides during berthing by 30-50% of the values generated without the provision of the display.

- For those forces generated in excess of 50% of the dynamic range of the sensor, visual display of the force/torque values reduce the duration of the application of that excessive force by 60-80%.

(ii) Task completion time:

- Task completion time was most dependent on the individual operator's control strategy. The directions stressed both accuracy and speed in task completion; however, speed was consistently sacrificed to performance accuracy.

- Provision of F/T information slightly increased the usual task completion time for a given operator. This was probably due to the requirement for shared attention between visual displays of payload position and the force/torque display.

- Several operators noted that the provision of the F/T display expedited trajectory planning in the case of excessive force application. The F/T information could be used diagnostically to identify the cause of the problem and to provide a basis for replanning the maneuver. This was especially true in the case of keel trunion misalignment; because the source of such an error is not readily visual available.

- As noted, the effect of the varied feedback conditions will be examined through analysis of the digital force/torque data.

2.2 Tool use and Simulated module change out

Task:

The tool use and module change out task involved manipulation of the modules of the task board illustrated in Figure 2. The flat screw driver blade was used to unlatch the box module and replaced in the appropriate receptical. The module was then grasped, removed and reinserted. The screw driver blade was then retrieved and used to latch the module back in place. The task was performed in the end effector control mode, in which the control and display was referenced to the end effector position, independent of its position in the shuttle bay. Figure 3b illustrates the coordinates of the end effector reference frame. Figure 1b illustrates the placement of the task box in relation to the shuttle bay.

Results:

It is significant to note that three of the four subjects were unable to compete the module extraction task without the provision of visual force and torque information.

Several representative figures have been abstracted from the analog performance record to illustrate typical performance profiles.

- Figure 4 shows the calibration scale for the data represented.

- Figures 5a-5b shows the basic extraction/insertion sequence. The generation of excessive forces and torques in the absence of the F/T display is illustrated in 5a. In fact, the trial was aborted when the forces were sufficient to damage the module during the test. Successful completion of the same task sequence is demonstrated in 5b.

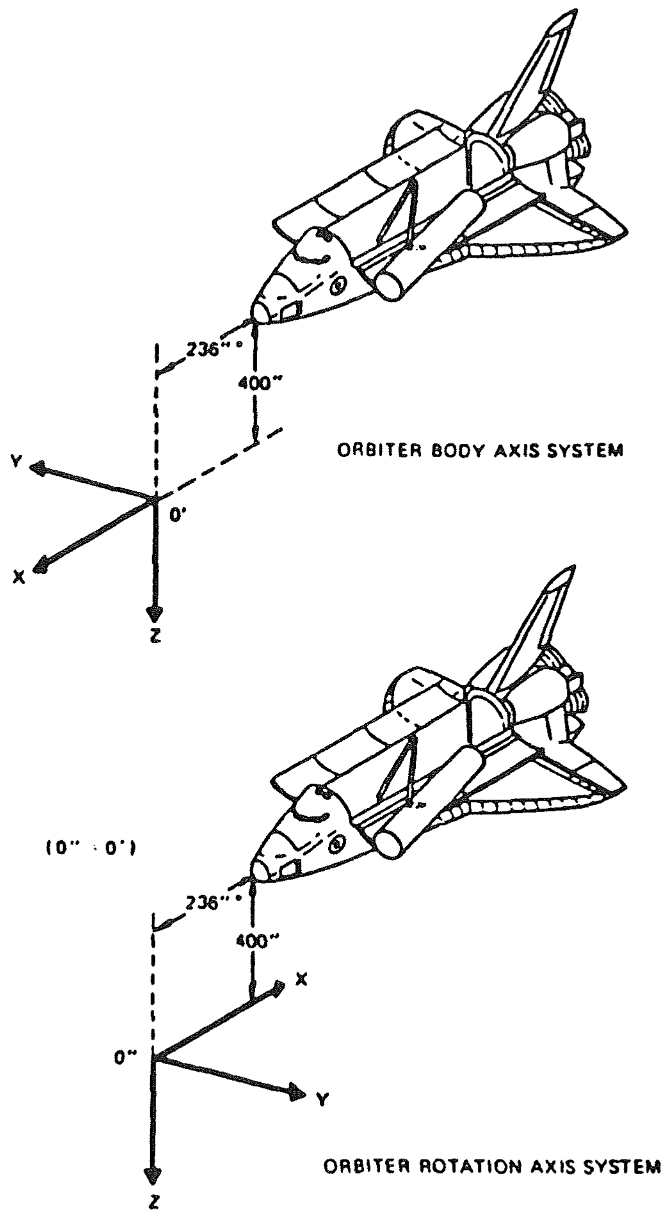
- Figures 6a-6b provide a direct comparison of module insertion sequences with and without the F/T display. A comparison of 6a and 6b illustrates increased levels of force/torque generation and increased task completion time for the single subject who was able to complete the module change out in the absence of the F/T display.

- Figure 7a provides a demonstration of a jam in which module extraction is aborted due to excessive force in the X and Y axis and torque about the Z axis. The diagnostic capability of the display is illustrated in Figure 7b, in which, despite the occasional generation of high force and torque values, the subject is able to successfully complete the module extraction.

- Figure 8a-8b shows successful force management in the tool use sequence of the task as a function of the provision of the force/torque display.

3.0 FUTURE RESEARCH EFFORTS

One of the major concerns in the presentation of force/torque information is the speed vs. cognitive information transmission dilemma. In other words, it is the dilemma of trying to transfer to the operator as much information as fast as possible without having a degradation of performance. This information should be presented so that the operator can cognitively understand and utilize it.



* For Orbiter 102 only

Figure 3a. Relationship between Orbiter Axis System and Orbiter Rotation Axis System

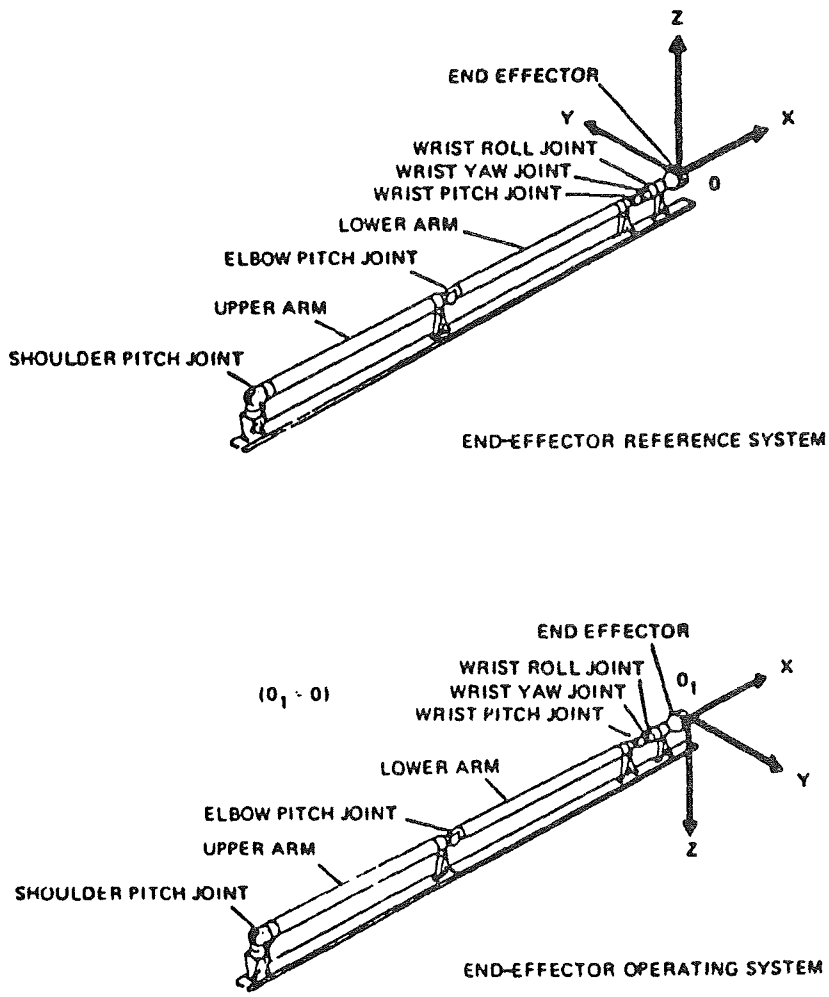
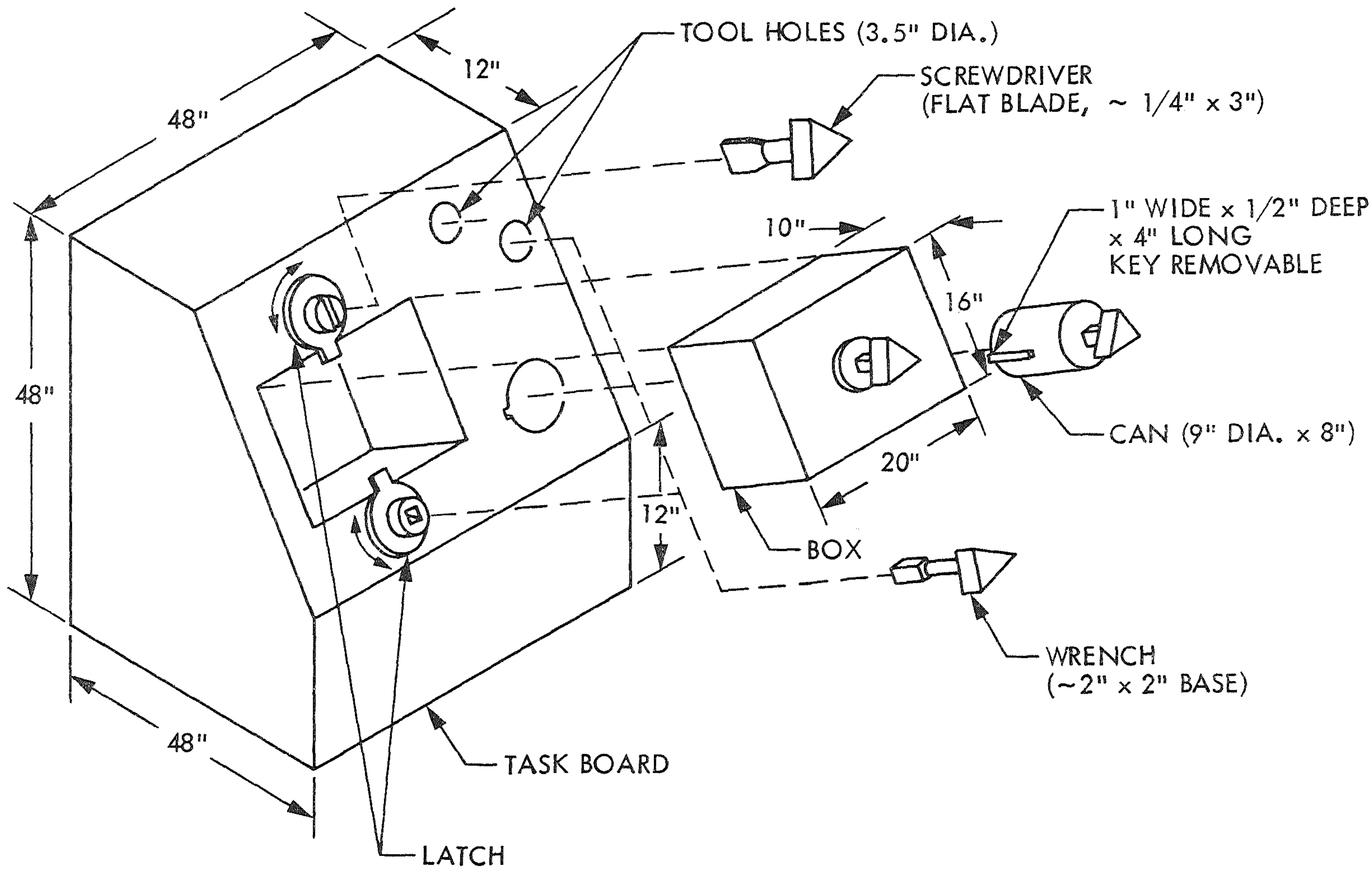
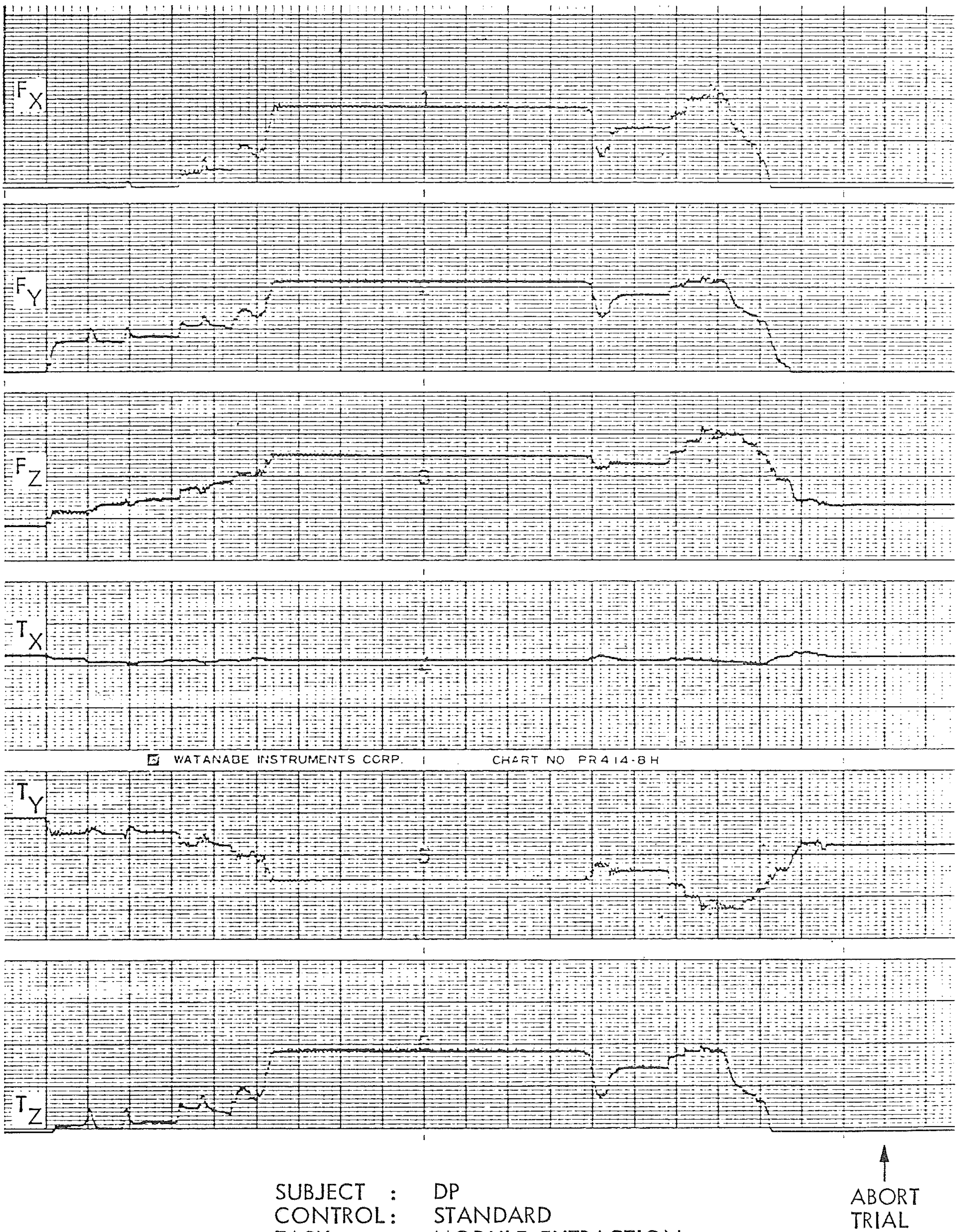


Figure 3b. Relationship between End-Effector Reference System and End-Effector Operating System



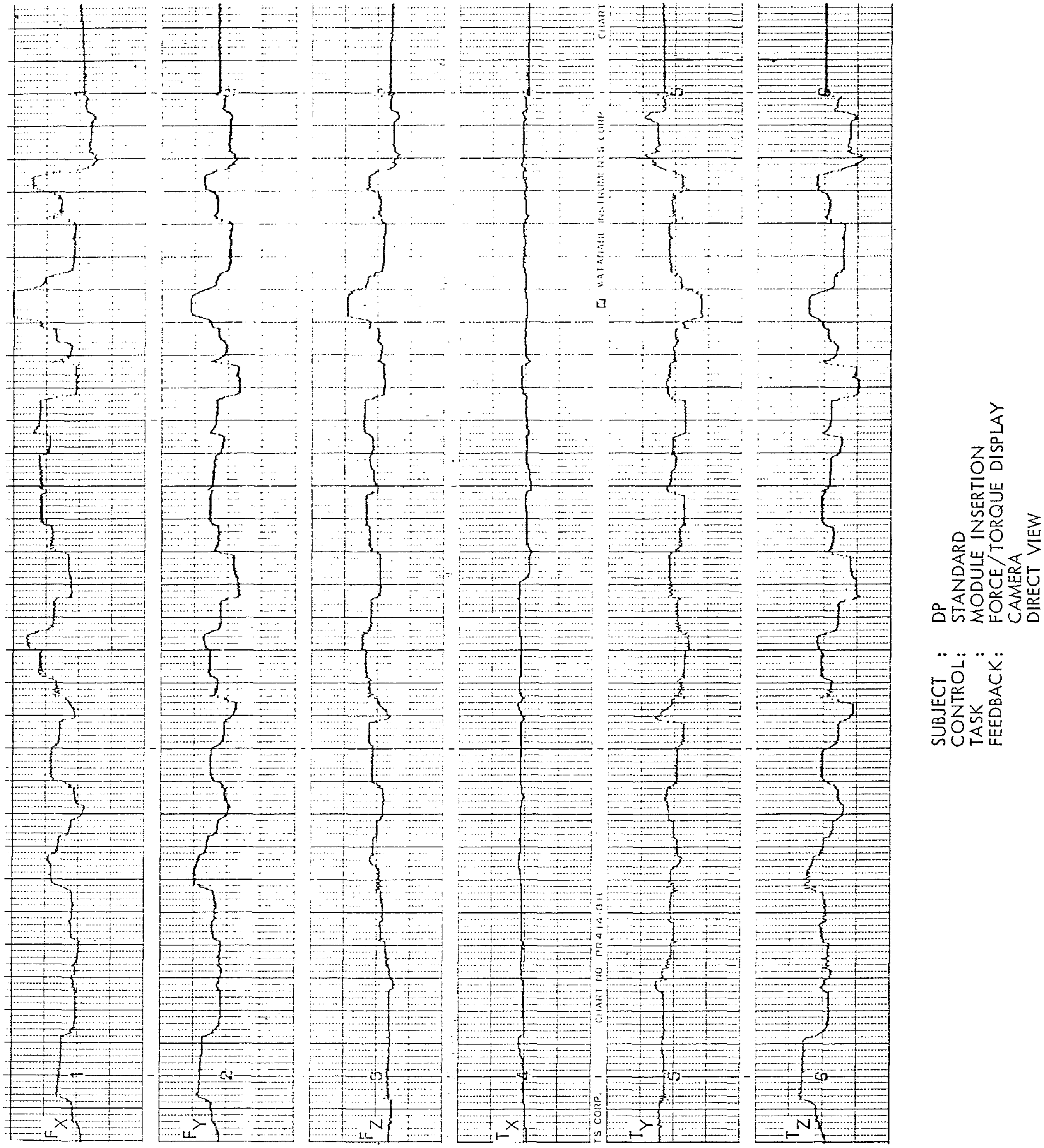
TOOL HOLES (3.5" DIA.)
SCREWDRIVER
(FLAT BLADE, ~ 1/4" x 3")
1" WIDE x 1/2" DEEP
x 4" LONG
KEY REMOVABLE
CAN (9" DIA. x 8")
WRENCH
(~2" x 2" BASE)
BOX
TASK BOARD
LATCH
48"
48"
48"
12"
12"
10"
16"
20"

Figure 4.



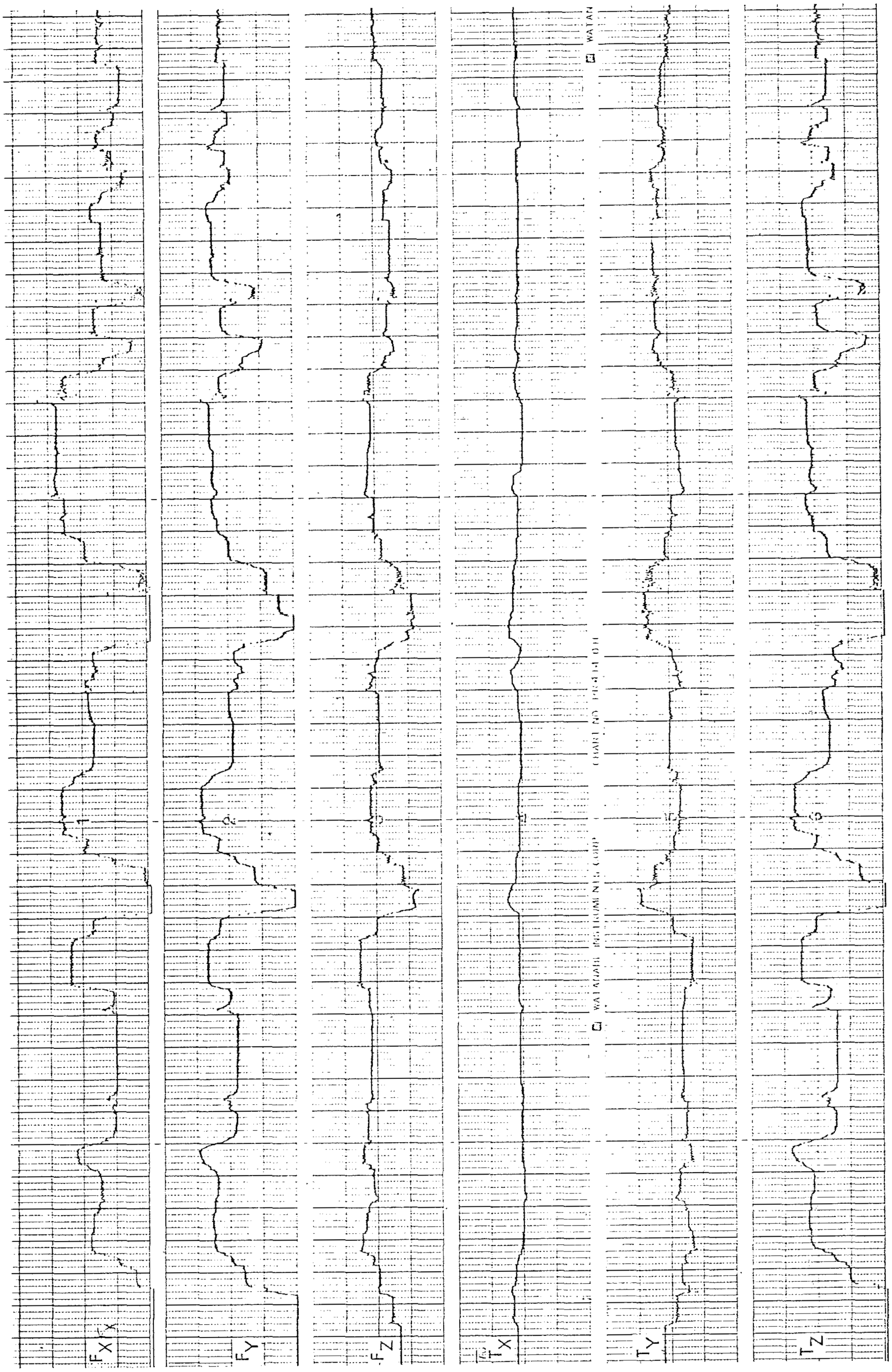
SUBJECT : DP
CONTROL : STANDARD
TASK : MODULE EXTRACTION
FEEDBACK : CAMERA
DIRECT VISION

Figure 5a.



F X
F Y
F Z
T X
T Y
T Z
SUBJECT : DP
CONTROL: STANDARD
TASK : MODULE INSERTION
FEEDBACK: FORCE/TORQUE DISPLAY
CAMERA
DIRECT VIEW

Figure 5b-1.



SUBJECT : DP
CONTROL: STANDARD
TASK : MODULE EXTRACTION
FEEDBACK: FORCE/TORQUE DISPLAY
CAMERA
DIRECT VIEW

Figure 5b-2.

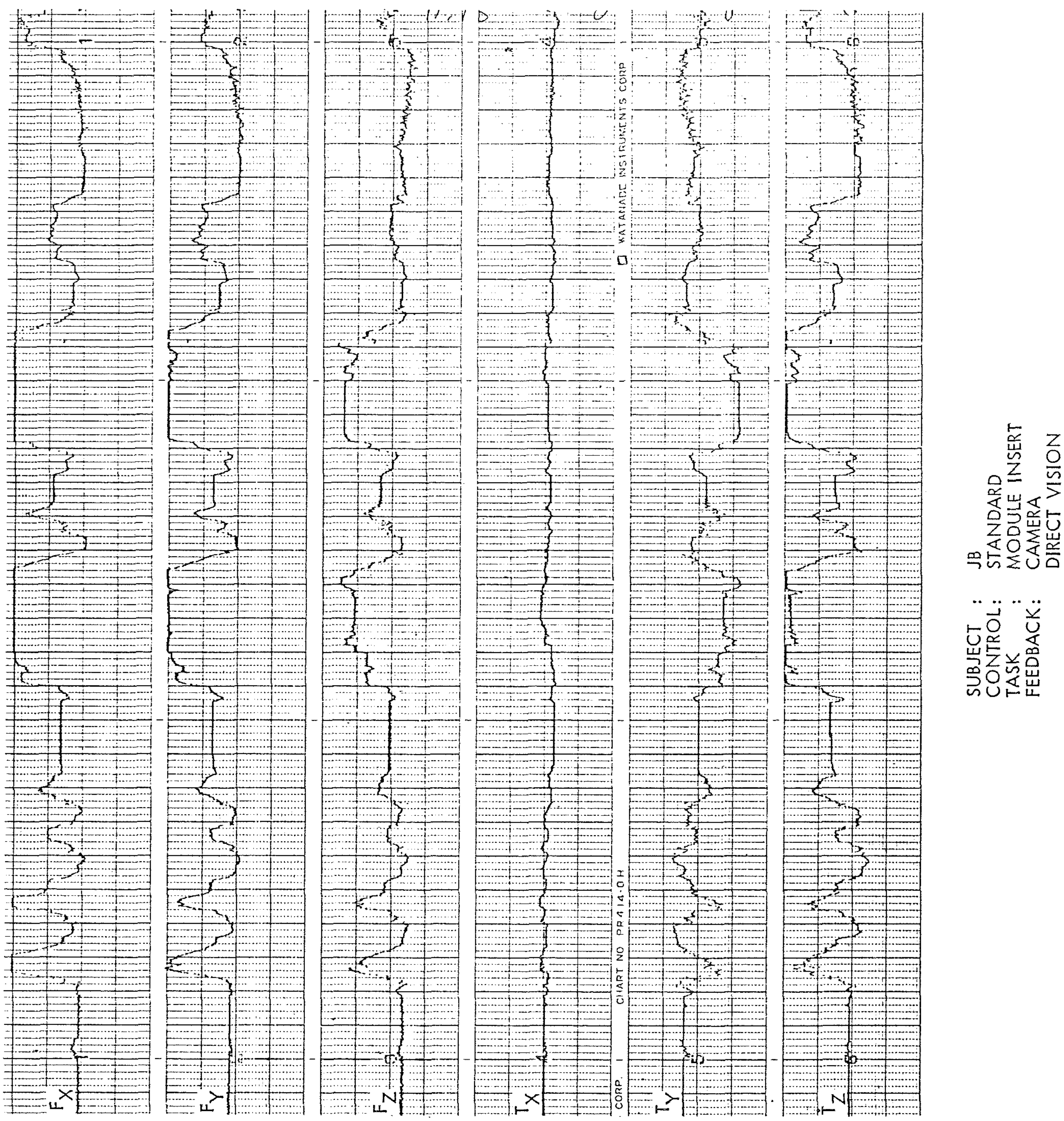
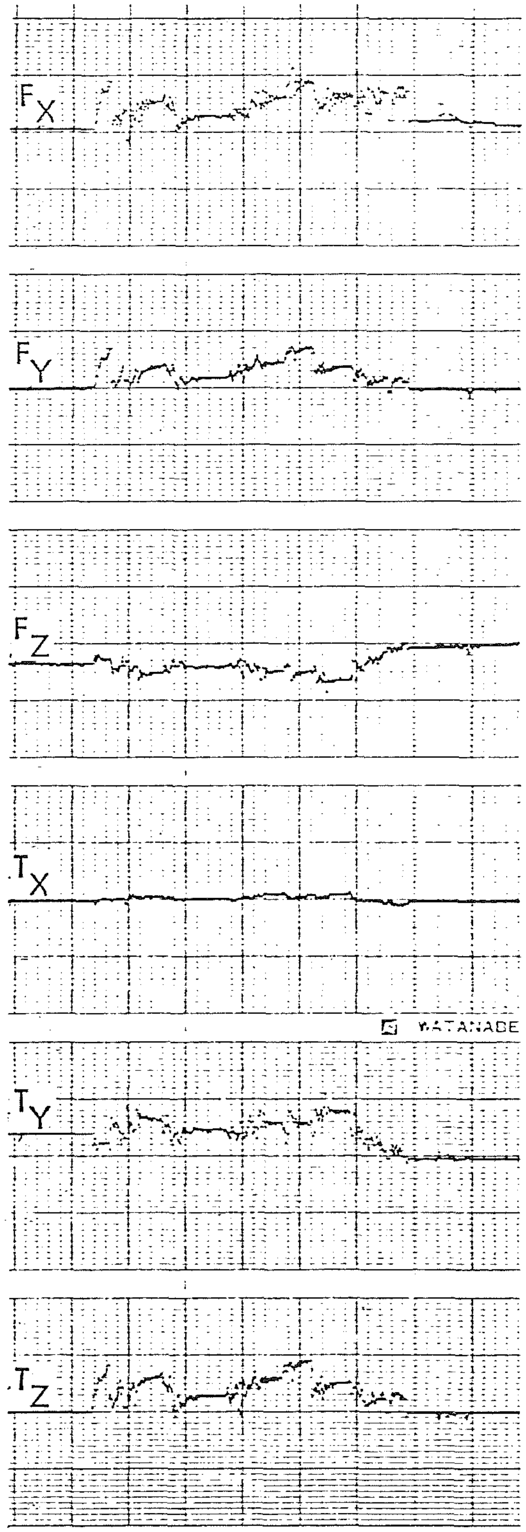

FX
FY
FZ
TX
TY
TZ
WATANABE INSTRUMENTS CORP
CHART NO PR414-0H
CORP
SUBJECT : JB
CONTROL: STANDARD
TASK : MODULE INSERT
FEEDBACK: CAMERA
DIRECT VISION

Figure 6a.



SUBJECT : JB
CONTROL: STANDARD
TASK : MODULE INSERTION
FEEDBACK: FORCE/TORQUE DISPLAY
CAMERA
DIRECT VISION

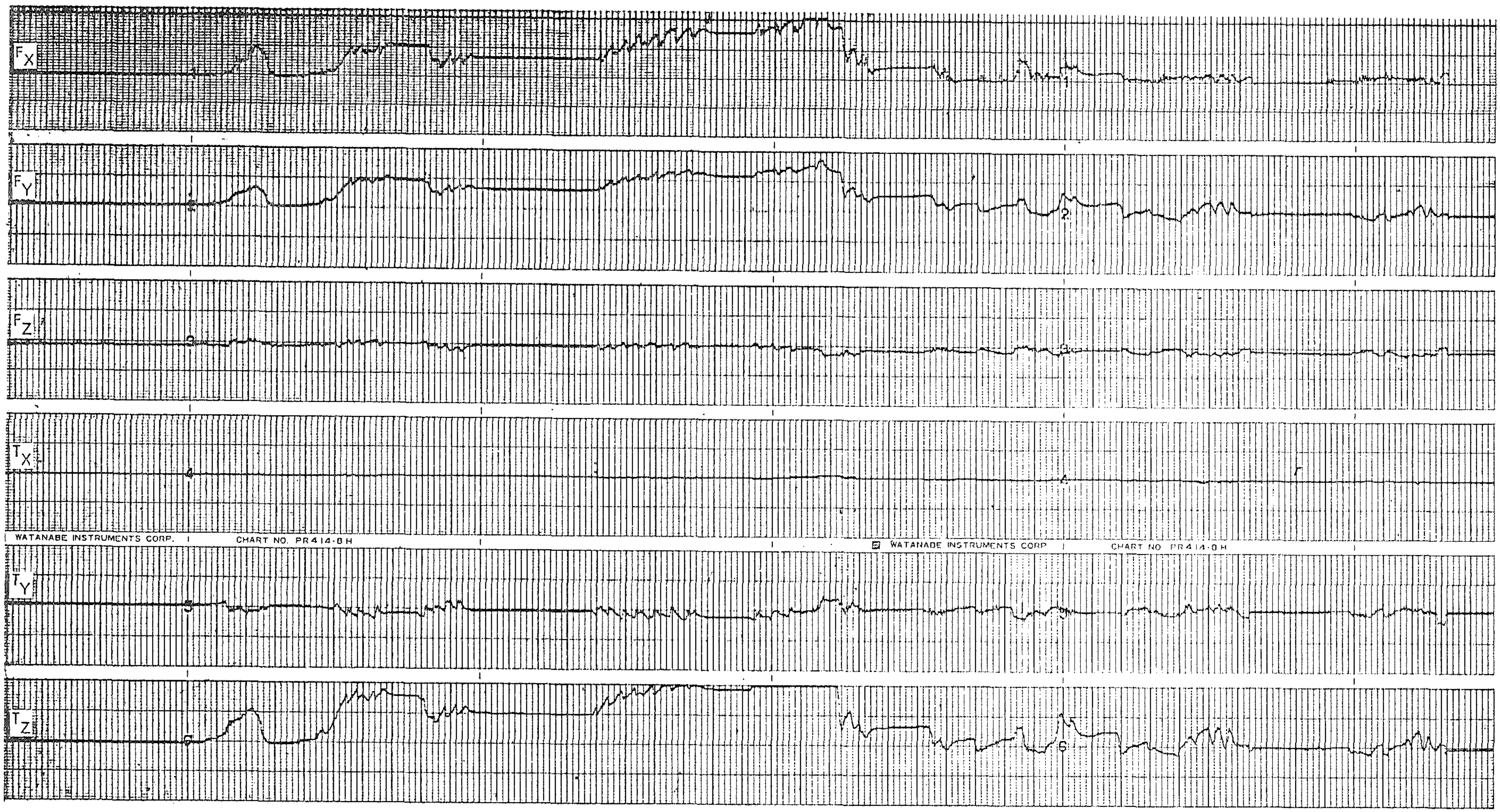
Figure 6b.

Fx
Fy
Fz
Tx
Ty
Tz
TEST ABORT
WATANABE INSTRUMENTS CORP.
CHART NO. PR414-8H
SUBJECT : JS
TASK : MODULE EXTRACTION/INSERTION
CONTROL: STANDARD
FEEDBACK: CAMERA
DIRECT VISION

Figure 7a.

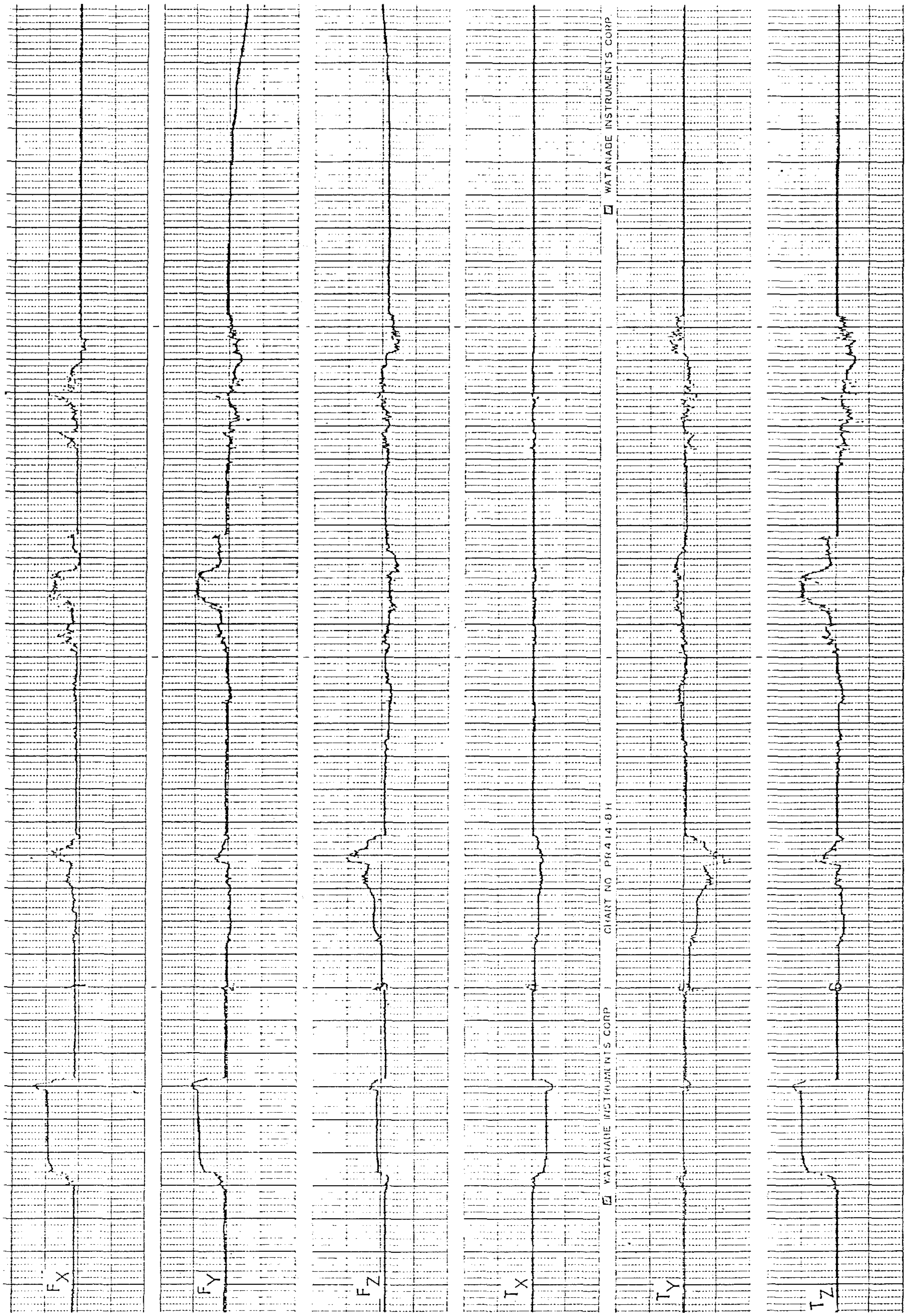
SUBJECT : JS
CONTROL: STANDARD
TASK : MODULE EXTRACTION/INSERTION
FEEDBACK: FORCE/TORQUE DISPLAY
CAMERA
DIRECT VISION

Figure 7b.



SUBJECT : PV
CONTROL: STANDARD
TASK : TOOL USE
FEEDBACK: CAMERA
DIRECT VIEW

Figure 8a.



SUBJECT : PV
CONTROL: STANDARD
TASK : TOOL USE
FEEDBACK: FORCE/TORQUE
CAMERA
DIRECT VISION

Figure 8b.

Items for display improvement:

i) The display should be as smooth as possible. The operator should be concentrating on the information present in the display, not on the display itself.

Most computer graphics display hardware is display-bound. The more pixels and polygons drawn on the screen, the slower the pixel write speed. Since most hardware internal graphics subroutines (draw rectangles, draw circles) are faster than software generated subroutines, it is optimal to use as many hardware oriented commands as possible.

ii) The display should present the information in a natural manner (i.e., true perspective view).

iii) Color should be used to enhance contrast between different display parts.

The true perspective 3-D Force/Torque display:

We have been able to make progress in the development of real-time 3-D displays because the substantial leap in the speed of current computer graphics hardware. The displays we used at JSC had a refresh rate of 4 to 5 hertz and there was a significant speed difference between the X/Y axis and the Z axis. With current display technology, a refresh rate of 30 hertz is easily achieved with much more true and complex display of forces and torques (Figure 9).

The torques and forces are color and directional coded. Red indicates a negative force or torque and blue indicates a positive force or torque. The torques follow the right-hand rule around the force axis. The display is projected in true perspective. The box around the display enhances the perspective image. The reticular marks divide the force bars into quarters. These marks help the operator gauge force on each axis. This is true especially in the case of the negative z force axis.

We thought about adding a grid on the bottom of the box to enhance the perspective image but it was decided that it would add too much clutter to the display.

4.0 CONCLUSION

In general, the operators considered the F/T display informative, and the data illustrate the fact that management of forces and torques improved when the display was used. In fact, the precision module extraction and tool use task was only able to be performed with the display aiding. There were a number of factors noted that could contribute to an improvement of the display format, and these have been the focus of our efforts in the development of the three dimensional perspective display. In particular, the following issues are being

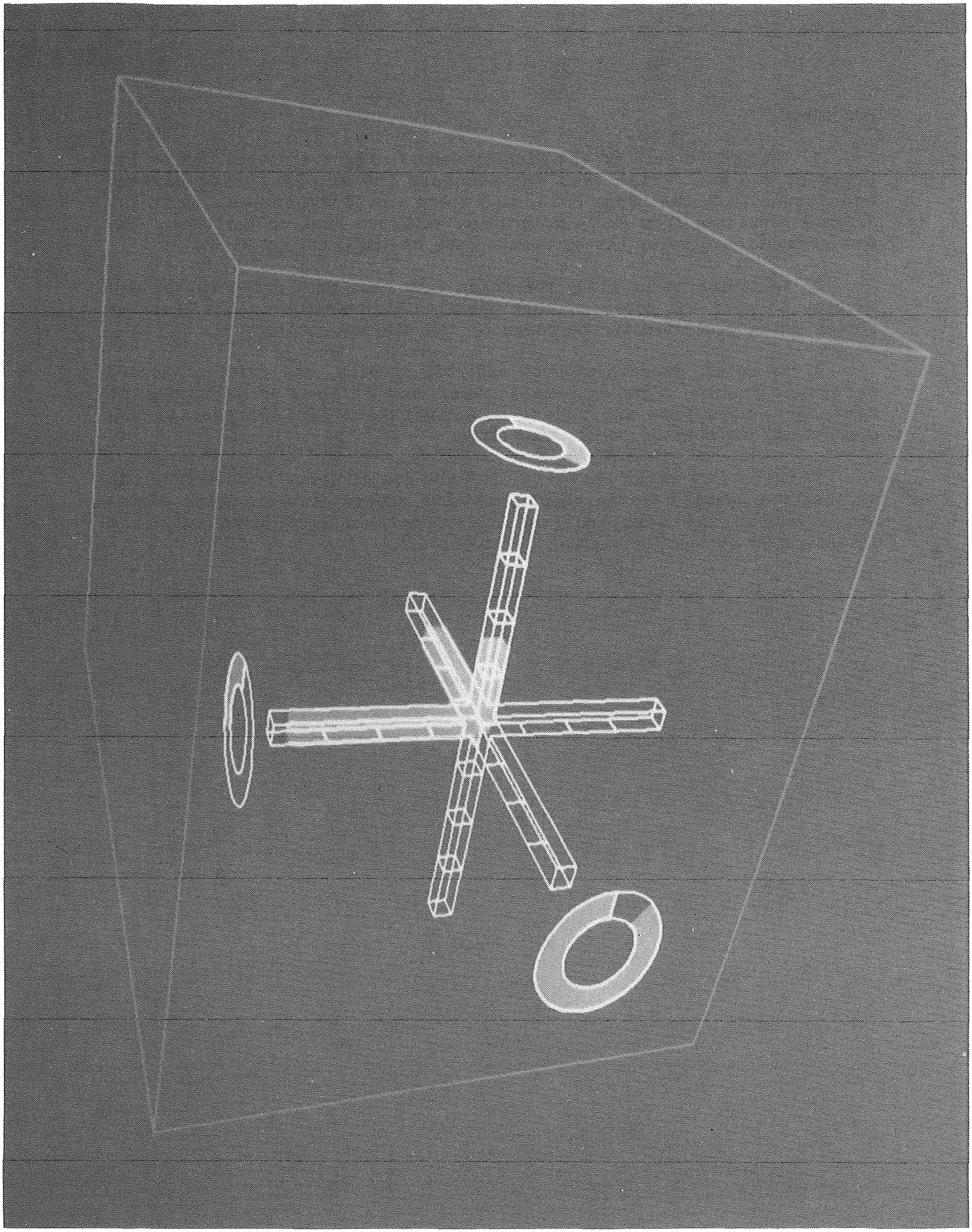


Figure 9. New Force-Torque Display

addressed:

1. The update rate of the display used in the evaluation was on the order of 4-5 Hz. While this was adequate for slowly moving payload operations with the large PFTA, there was a noticeable jumping in the display resulting from force generation with the smaller payloads. The new generation display has an update rate on the order of 30 Hz.

2. Reticular marks along the frame axes have been added in the new display to give the operator more detailed information on the level of forces being generated in the range of the display scale.

3. As noted, coordination of control, display, and point of regard reference frames is being investigated in an effort to maintain the operator's situation and reduce disorientation in interpreting the operational effects of force generation.

4. There is a great potential for the use of color to increase the information density of the display without adding clutter. Color coding of direction and magnitude of the force/torque vectors is being investigated in the new display development.