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SATELLITE TEST ASSISTANT ROBOT (STAR)[1]

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ABSTRACT

A three-year, three-phase program to demonstrate the applicability of telerobotic technology to the testing of satellites and other spacecraft has been initiated. Specifically, the objectives are to design, fabricate, and install into the JPL 25-ft. Space Simulator (SS) a system that will provide the capability to view test articles from all directions in both the visible and infrared (IR) spectral regions, to automatically map the solar flux intensity over the entire work volume of the chamber, and to provide the capability for leak detection.

The first year's work, which provides a vertically mobile viewing platform equipped with stereo cameras, will be discussed. Design constraints and system implementation approaches mandated by the requirements of thermal vacuum operation will be emphasized.

INTRODUCTION

Telerobotics in the general domain of space applications has had a difficult time in attracting the support of a user community. This is not surprising; flight system managers tend to be very conservative technologically, and rightly so. No flight system manager is likely to be willing to put at hazard his budget and schedule in order to incorporate into his program new and unproven technologies that are not essential to his primary mission objectives.

To break this impasse, it will be necessary for spacecraft program managers to see the capabilities of telerobotics in action, and to be able to judge the maturity of the technology, in a non-threatening environment. One such environment that could have high visibility to spacecraft managers, but still be non-threatening, is spacecraft testing.

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The STAR program was devised to fill an observed need (for a greater degree of automation and more flexibility) in the spacecraft testing arena. It was proposed to Code R as a joint effort between the telerobotics technologists and those responsible for spacecraft testing, as a means for introducing technology developed under the aegis of the Telerobotics Program into a flight program environment in a manner that would be non-threatening to flight articles. At the same time it presented to the Code R program the challenge of designing to an environment close to that of space. The emphasis in the program therefore is on the detailed engineering required to adapt known technology to the harsh environment of space. It is the flavor of that detailed engineering that this paper attempts to convey.

GROUND RULES

The two ground rules that guided the conception of the program were:

(1) the effort should showcase technology developed by Code R as part of the Telerobotics Program; and

(2) the product should be sufficiently attractive and non-threatening to the user community that they would be willing to incorporate it into their test plans.

To satisfy these ground rules a joint effort was initiated between the telerobotics technologists and the spacecraft test engineers to identify those needs that might best be met by telerobotics technology. An obvious target was test operations in the large space simulators in which spacecraft system testing is conducted. Here, where the test article is inaccessible during test, and where gaining access to the test article is both expensive and time-consuming, it seemed that telerobotic techniques could prove valuable in assisting the test operations. A crude estimate indicated test cost savings of a quarter of a million dollars per year might be anticipated. One major constraint was immediately recognized, however: nothing (and certainly no robotic element) would be allowed to penetrate the work volume of any spacecraft while it was in the chamber. Thus, any assistance during test operations would be limited to remote sensing. Even with this constraint, however, there were immediately identified a number of functions that telerobotics-developed technology might supply.

Remote observation- direct observation of test articles is extremely limited. In order to provide a uniform thermal background, the number and size of observation ports in the two major JPL test chambers has been kept to a minimum, and the viewing angles available are far from ideal. This has been somewhat compensated in recent years by cameras mounted in the chamber, but these have been in fixed locations. The ability to observe the test article from all angles, at varying degrees of magnification, and in stereo, was identified as a highly desirable capability to have.

Remote temperature sensing- presently spacecraft are instrumented with hundreds of thermocouples to provide verification of thermal models. If an IR camera could be mounted to provide viewing of the test article from any and all angles, a great deal more data could be generated with a great deal less effort. IR sensing of the test article from the movable pan/tilt platform was also identified as a desirable capability.

Solar intensity mapping- obtaining a map of solar intensity throughout the chamber is a cumbersome and laborious process as presently implemented. Automation of this measurement, which is carried out generally only when no test article is present, would be another desirable feature for any system to be installed in the chamber.

Leak detection- pinpointing leaks in the shroud when they occur is a very difficult and time-consuming task, involving going over the surface with helium leak detectors. Any automation of this function, which would result in reduction of chamber down-time, would be very useful. It was estimated that this alone could save $120,000 per year.

Having identified a list of potential functions, a design concept for a system to provide those functions was generated, and is shown in Figure 1. A program was then outlined that would allow a phased development of capability, with checkpoints along the way that would allow periodic reevaluation of both objectives and progress. Providing users with an early demonstration of the potential advantages of the technology was an important aspect of the program, which was proposed in three phases:

Phase 1- FY '92- Demonstrate in the JPL 10-ft SS an improved viewing capability with a Z-axis-movable pan/tilt platform on which a stereo vision system is mounted. (Because of previously scheduled modifications, the 25-ft SS will not be available for STAR installation until the end of FY 93.)

Phase 2- FY '93- Install the system into the 25-ft SS, and add the IR camera and the solar spot mapping capability.

Phase 3- FY '94- Add capability for azimuthal motion of the platform, and leak detection capbility.

This paper presents the Phase 1 effort.

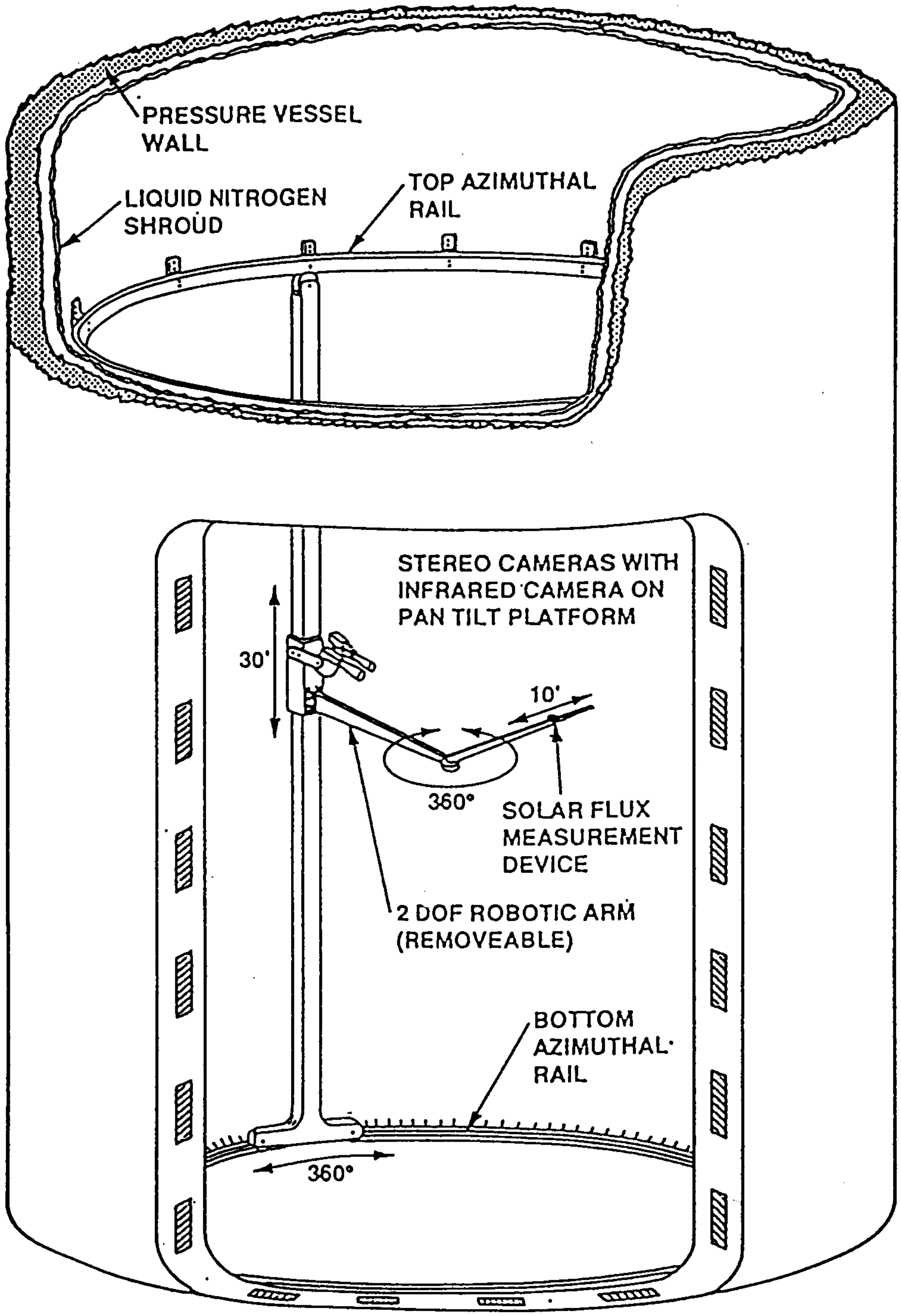

Figure 1. Initial Concept for the STAR System

MAJOR DESIGN CONSIDERATIONS

The basic concept for the system as outlined above is quite straightforward. Complications quickly arise however when specific requirements related to the application are taken into consideration. First and foremost of these is the environment in which the system will have to operate.

For STAR, the application environment includes high vacuum, i.e., on the order of 10^{-7} torr, and temperatures ranging from -196° C to +93°C. (It should be noted here that for the Phase 1 demonstration there will be no cold shroud in the 10-ft SS. However, since the same hardware is to be ultimately installed in the 25-ft SS, the design temperature range must accommodate that application.) Hard vacuum operation imposes stringent cleanliness requirements, since no significant outgassing can be tolerated, both in terms of maintaining vacuum, and in avoiding contamination of the test article. Further, rubbing surfaces are to be avoided, since they tend to produce particulates which can then deposit on sensitive surfaces. The large temperature range means that there will be significant dimensional changes in all components; these changes will of course be a function of the materials used. The design must address these considerations in detail.

Another important design consideration for this application is that the system must not significantly disturb the environment seen by the test article, as, for example, by presenting a warm spot in the otherwise uniformly cold wall surrounding the test article, or by presenting a source of glare that might confuse spacecraft optical components. This means that all heat sources, such as the drive motors, or cables that are dissipating heat, must be shrouded from the direct view of the test article. By the same token, shiny surfaces are not desired. The design must recognize these constraints.

A third design consideration is reliability and ease of maintenance. Since one of the major drivers for this program is the promise of decreasing the amount of down-time in testing, it would be counterproductive to have to halt testing to repair this equipment, or, when repairs or maintenance are required, to make it so awkward or time consuming to accomplish them as to defeat the purpose of installing the system in the first place.

A consideration notable for its absence from this list is extreme accuracy. Unlike most robotic applications, positional accuracy is not a strong requirement for the STAR system. To have position knowledge and repeatability accurate within a centimeter or two was judged to be quite adequate for this application. Since this is well within the capabilities of even the crudest mechanization, it was not a driver in the design.

PHASE 1 SYSTEM CONCEPT

A block diagram of the STAR Phase 1 system is given in Figure 2. It consists of the following assemblies:

a. The drive assembly,

b. The beam assembly,

c. The carriage assembly,

d. The pan/tilt assembly

e. The camera assembly

f. The in-chamber cable assembly,

g. The external cable assembly, and

h. The control console

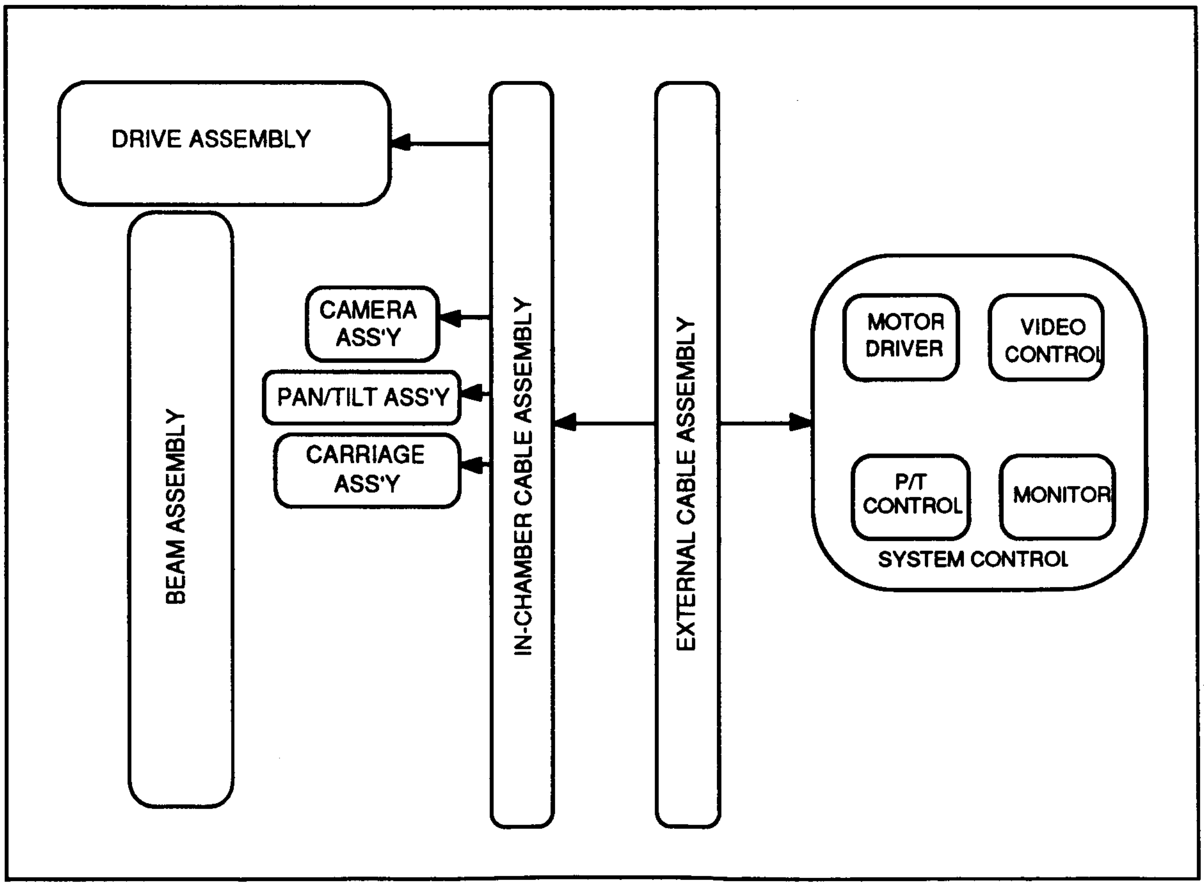

FIGURE 2. STAR SYSTEM BLOCK DIAGRAM

Table I

Comparison of Candidate Drive Mechanisms

CHARACTERISTIC \ MECHANIZATION	RACK AND PINION	LEAD/BALL SCREW	CHAIN DRIVE	CABLE DRIVE	METAL BELT DRIVE
A. MATERIALS					
Properties at Cryo Temps	3	3	4	2	1
Properties over Wide Temp Range	4	4	4	2	1
Vacuum Rated	2	2	4	4	1
Non-Outgassing	2	2	3	4	1
Availability (Stock or Gustom Comp)	2	4	3	3	3
Overall Mass	4	5	2	1	1
Comparitive Reliability	3	2	4	4	3
Est. Development Time	2	3	3	3	3
Simplicity of Assembly/Install.	3	4	3	2	1
Maintainability	3	4	4	3	2
Overall Cost	2	5	3	1	2
B. CLEANLINESS					
Lubrication Required	4	4	4	1	1
Rubbing vs. Rolling Contact	3	4	4	3	1
Ease of Cleaning	3	4	4	5	1
Debris Generation	3	3	4	3	1

1- BEST SELECTION 5- WORST SELECTIOI

Table II

Major Design Analyses Conducted

Rail/Linear Bearing		Beam/Roller
Open Belt		Closed Belt
Electrical Cable Spool		Rolling Loop
Pulley Diameter	vs	Belt Stress Belt Width Belt Thickness
Roller Diameter		Hertzian Contact Stress
Counter-Balanced		Non-Counter-Balanced

For each of these assemblies a number of design approaches were available; space does not allow a discussion of them all. In the following paragraphs the most significant design choices will be presented, with an indication of the rationale behind the choice. Emphasis is given to the in-chamber portion of the system, since that external to the chamber (external cabling and control console) presented no special design problems.

DESIGN DESCRIPTION

a. Drive Assembly

The drive mechanism is the heart of the design, and was the most difficult to design within the constraints imposed by the environment. Its design also drove the design of most of the other system assemblies. It will serve as an example of the kinds of analyses that were required to validate the detail design.

For the Phase 1 effort the final product is to be a vertically moving carriage on which will be mounted a pan/tilt platform. Any number of options were available to provide the vertical motion, including rack-and pinion, cable, chain, lead or ball screw, metal belt/pulley, etc. Each of these has its own peculiar advantages and disadvantages. Some of the most obvious are listed in Table I for various candidate mechanizations. Scanning Table I, and in light of the design considerations given above, the metal belt/pulley system appeared to provide the best match for the requirements. It is compatible with the design requirements of vacuum operability over an extreme temperature range and high cleanliness, it is potentially lightest in weight, and the simplicity of the concept makes its implementation appear reasonably economical. With little time to pursue in-depth trade-off studies, this approach was selected early as the baseline for STAR. Emphasis then shifted to the next layer of questions, i.e., what would it take to make it work. Questions of materials selection, accommodation for thermal expansion/contraction, unlubricated operation, avoidance of sliding contacts, cable accomodation, etc., required addressing in detail.

Table II lists some of the more significant design analyses required to come up up with a design that would meet all requirements. A detailed exposition of all the trade studies performed is beyond the scope of this paper; only the highlights and major conclusions will be reported here.

Drive Train

The selected motor is an Inland Brushless DC motor, Model RBE04500, flight and vacuum rated at 1000 in-oz of torque and for -55°C operation. It was selected specifically because it is designed for vacuum operation. A worm gear drive was selected because of its inherent non-backdriveability; while it violates the design criterion of no rubbing contacts, the rule was violated in this one case because it provided the additional advantages of a high gear ratio and smooth operation. The selection of materials (bronze for the worm gear and steel for the drive gear) should minimize particulates generated by the rubbing motion. Even so, the drive will be totally enclosed in a housing to minimize the potential contamination that might be generated by this gearing.

Belt and Pulley

A primary concern was the selection of a belt material that could withstand the extremes of temperature and maintain high strength without embrittlement. An associated question was the diameter of the pulley, to minimize the bending stresses on the belt without violating the constraints of the maximum envelope allowed for the mechanism. Only solid belts were considered; woven belts, though far more amenable to the temperature extremes, were rejected because their (huge) surface areas posed too great a threat for contamination.

A survey of belt manufacturers uncovered no one who was willing to certify their belts for the specific environment we specified. However consultation with metallurgists indicated semi-hard 304 stainless steel should have the desired characteristics. A quick (though not highly scientific) test program involving flexing 304 stainless steel belts in liquid nitrogen and examining them for cracks verified this choice, which became the baseline. A further series of analyses on bending stress and yield strength as a function of bend radius and belt thickness led to the design parameter selection shown in Table III, which provides a design margin of about a factor of four for the maximum anticipated load of 100 lbs. However, to provide redundancy and an added margin of safety, a two belt system has been baselined.

TABLE III

Metal Belt Parameters

BELT LENGTH	320 INCHES
BELT WIDTH	2 INCHES
BELT THICKNESS	0.008 INCHES
BELT MATERIAL	304 SS COLD-WORKED 1/2 HARD
FATIGUE STRENGTH (100,000 CYCLES)	115,000 PSI @ 20°C 155,000 PSI @ -196°C
TENSILE STRENGTH	195,000 PSI @ 20°C 260,000 PSI @ -196°C
BELT CYCLIC LOAD CAP.	1400 LBS @ 20°C
BELT STATIC LOAD CAP.	3100 LBS @ 20°C

A final design decision was made to leave the belts open-ended. This automatically maintains belt tension as thermal expansion and contraction changes belt length, without the need for additional tensioning devices.

The baselined pulley/drive train system is shown in Figure 3, and, as an exploded view, in Figure 4. Figure 5 is a photograph of the actual hardware after initial assembly.

b. Beam Assembly

The selection of a belt and pulley drive allows the use of a simple and inexpensive U-beam for the vertical member. The beam is supported at the top only; the bottom is pinned via slotted holes to allow for thermal motion while maintaining verticality. The selected beam is 4 in. by 12 in., 6061-T6 aluminum, with 0.29 in. wall-thickness, black anodized, and for the initial demonstration is 25 feet long. Nothing in the design limits the beam to this length, however, and the basic design is fully adaptable to the larger 25' space simulator by using a longer beam.

The beam assembly is shown in Figure 6. The depth of the beam has been chosen to comfortably house the rolling loop cable that supplies power and signal connections to the carriage. A cover, split to allow passage of the wiring, is provided to shield the wiring from the chamber and to present to the chamber as uniform a temperature environment as possible.

c. Carriage Assembly

The primary design challenge for the carriage assembly was to provide free motion with minimum friction and no binding over the large temperature range and in high vacuum. As noted earlier, this eliminated from consideration any design that requires sliding contacts. The selected design, shown in Figure 7, provides six sets of wheels. Two sets (top rear and lower front) are load-bearing, while a second set (top front and lower rear) are spring loaded to assure contact is maintained. An additional set of wheels, also spring-loaded, is mounted to each side to maintain alignment as the beam changes dimensions during thermal cycling. Vespel has been selected as the wheel material to minimize the possibility of contamination by metal particulates that might be generated from the rolling contact of the wheels with the beam. Bearings are 440C stainless steel, and are unlubricated.

A major feature of the carriage is the ease with which the assembly can be removed. Loosening four bolts that secure the wheel assemblies, unfastening three electrical connectors, and pulling a single release pin from the belt yoke allows the entire carriage and instrument payload to be lifted off as a unit.

d. Pan/Tilt Platform

A pan/tilt platform previously used in the space simulator was available for at least temporary use with this system. This platform is shown in Figure 8.

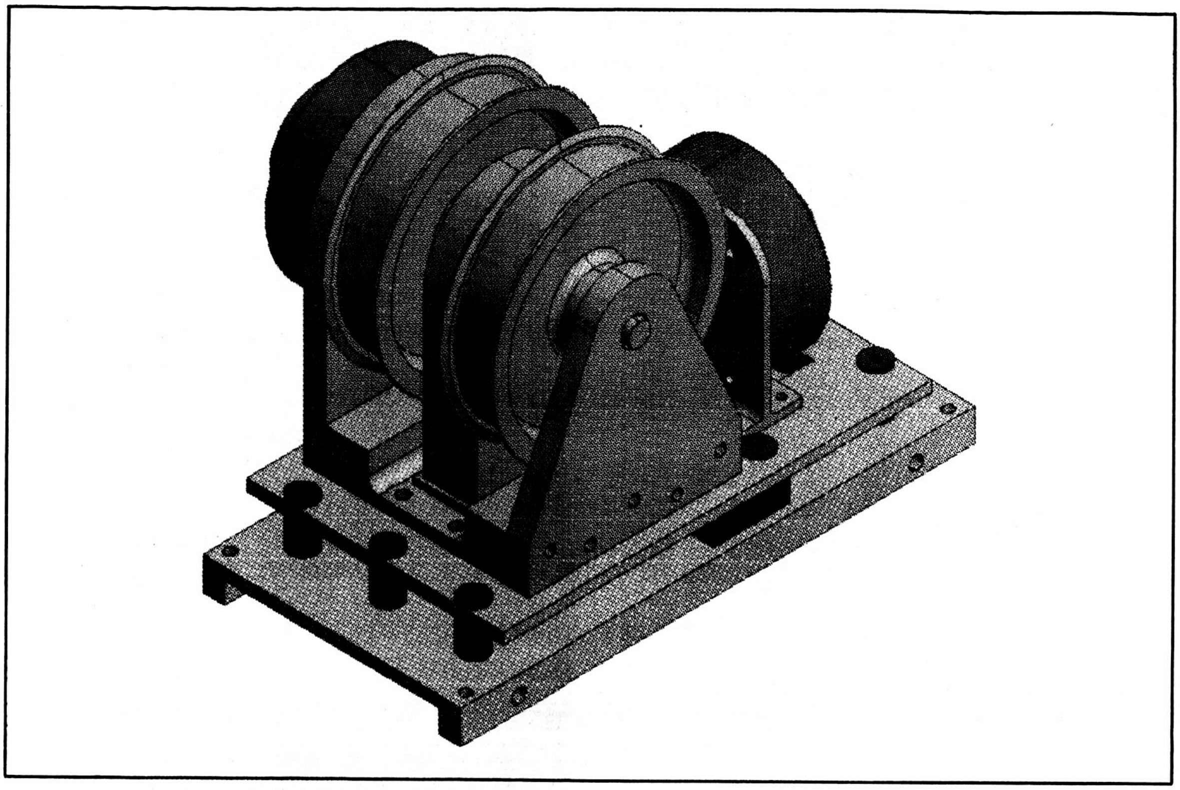

Figure 3. Perspective View of the Drive Assembly

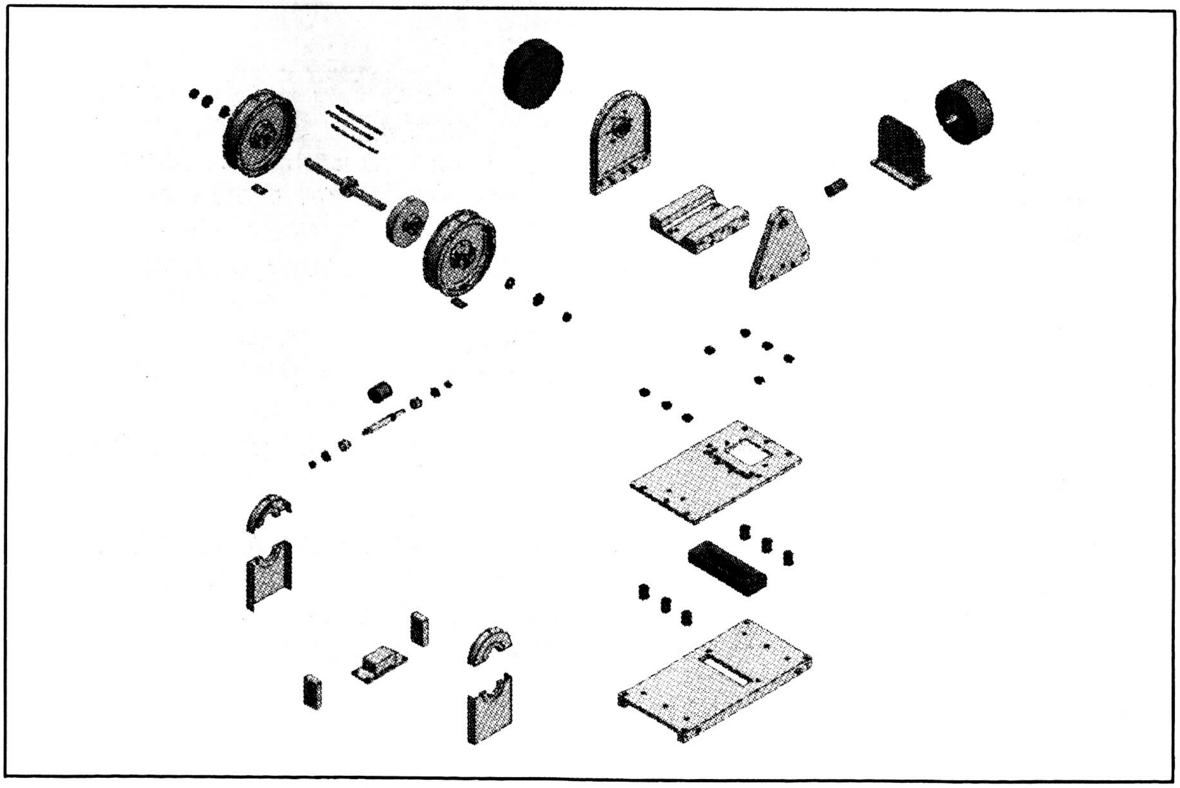

Figure 4. Exploded View of the Drive Assembly

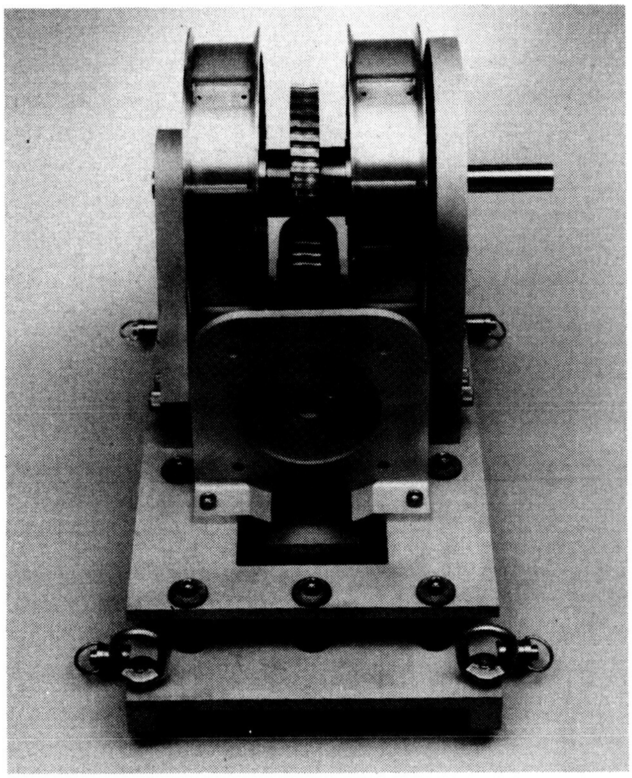

Figure 5. The Drive Assembly Hardware

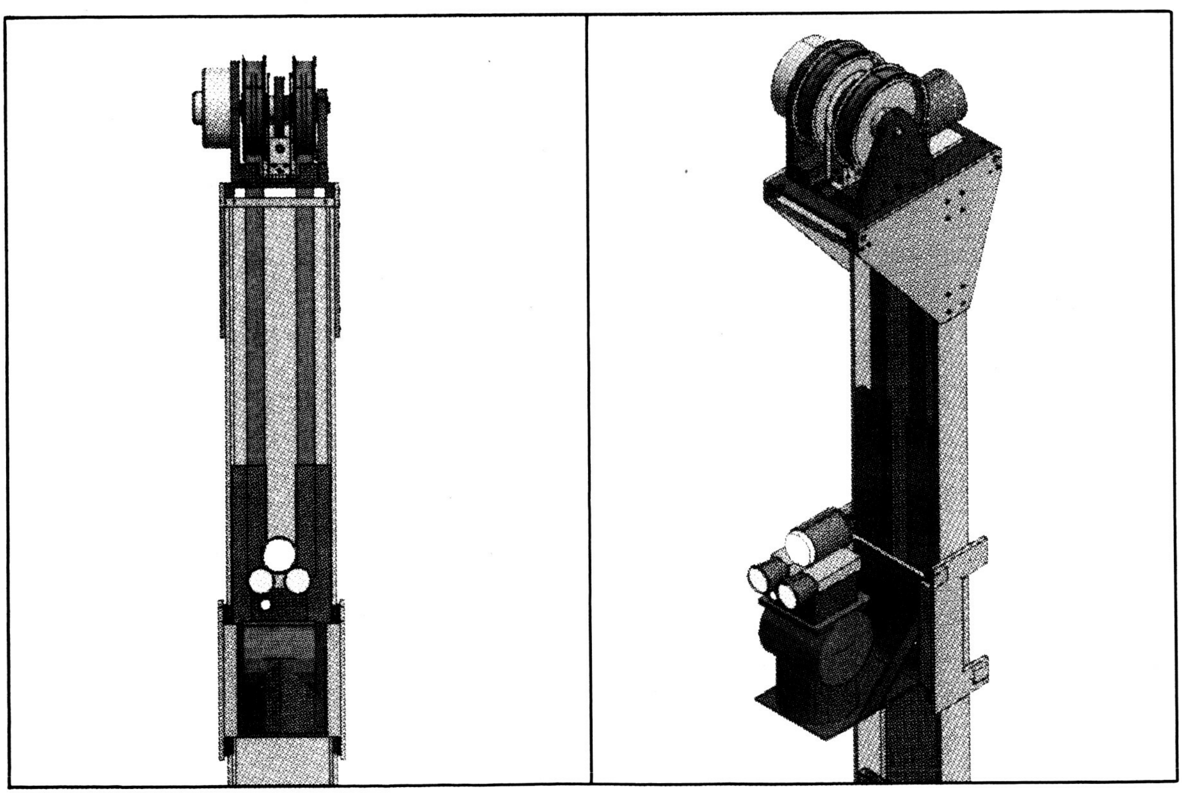

Figure 6. The Beam Assembly

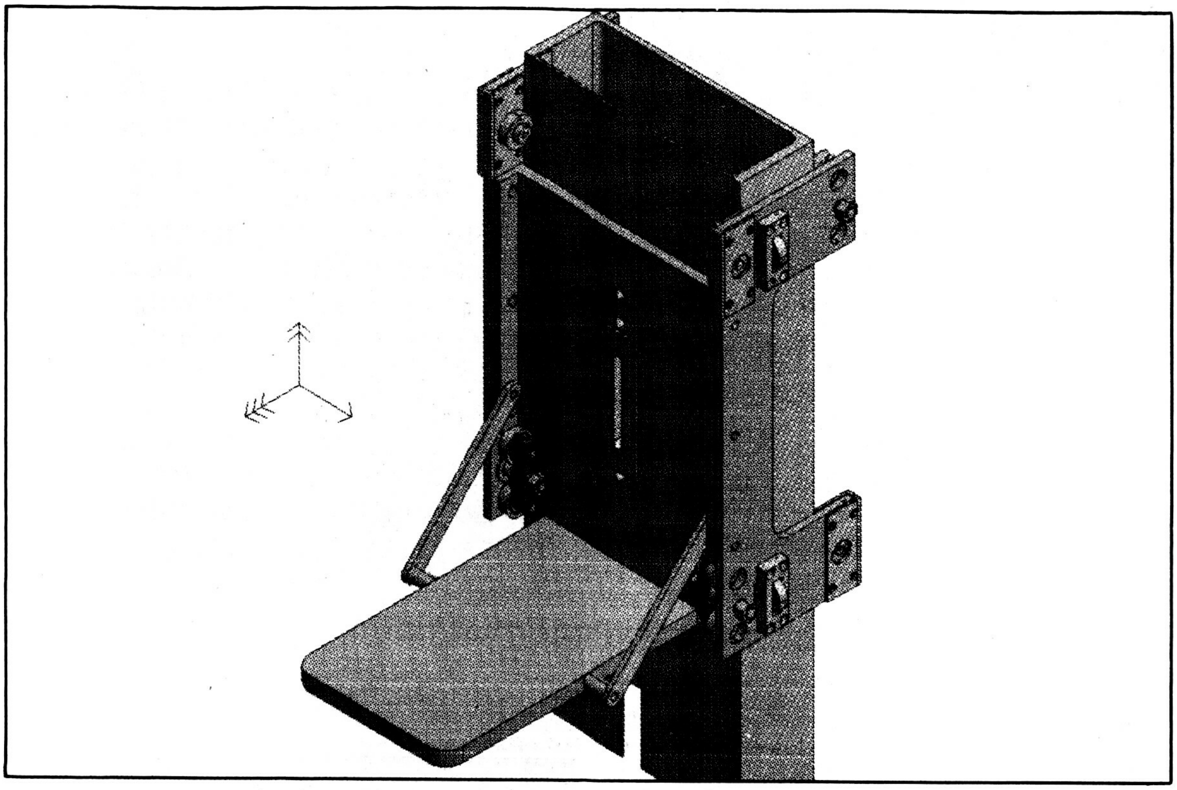

Figure 7. The Carriage Assembly

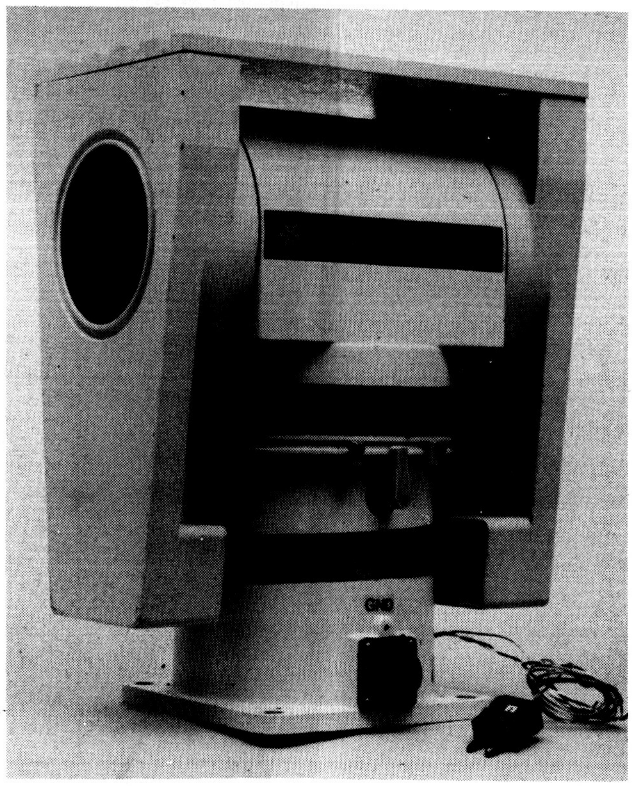

Figure 8. The Pan/Tilt Platform

e. Camera Assembly

The capability to be demonstrated in STAR Phase 1 is stereo viewing of the test article. To provide useful stereo over a reasonable range of target distances from the cameras, and to provide close-in viewing when required, a three camera arrangement, as shown schematically in Figure 9, taken from Ref 1, has been selected. The salient parameters for the camera arrangement for the Phase 1 demonstration are given in Table IV, also taken from Ref. 1. The cameras selected are designed to be vacuum operable, and will operate at temperatures as low as -50°C. To maintain them at this temperature will require thermal blanketing.

Cameras 1 and 2 have identical fixed focal length lenses, with manually adjustable focal distances. For any given test, these will be fixed prior to chamber evacuation. Camera 3's lens will be remotely adjustable for focal distance, and will serve as the best focused lens for both near and far stereo viewing.

The system will allow monocular camera viewing by any camera, and stereoscopic viewing by any pair of cameras. The video switcher will allow any camera image to be viewed on any of the three monitors.

A comprehensive discussion of the stereo system design process used here can be found in Ref. 2.

Table IV

Camera Configuration Parameters for the 10' Simulator

CAMERA PAIR	INTER-CAMERA DISTANCE	MONITOR #	MONITOR DIAG. SIZE	CONVERGENCE DISTANCE
1,2	5.6 INCHES	1	16"	2.2 METERS
2.3	2.5 INCHES	2	22"	1.6 METERS
1.3	3.1 INCHES	3	20"	3.0 METERS

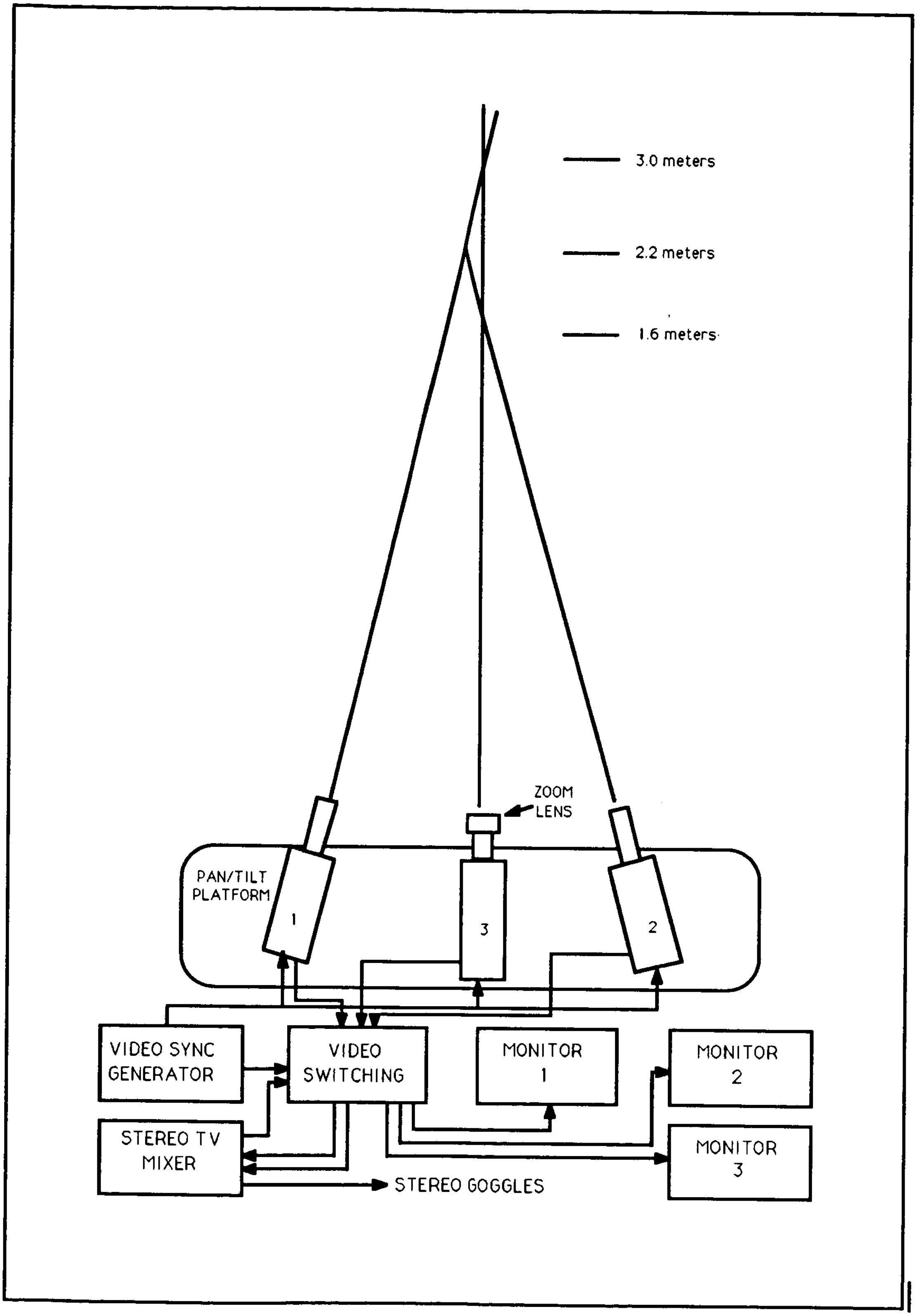

Figure 9. Camera Arrangement for the 10' Simulator

f. In-Chamber Cable Assembly

The overall schematic of the in-chamber cabling is shown in Figure 10. The only significant question here was the selection of cables for connecting the carriage and its payload to the chamber feed-throughs. To accommodate the motion of the carriage a rolling loop is employed. The cable, which is laid inside the beam, may reach temperatures close to -196°C. Again, no manufacturer was willing to guarantee the integrity of insulation flexing at such temperatures. Tests were run, flexing various flat cables with insulation rated for vacuum operation in a liquid nitrogen bath. In this testing, teflon insulated cables proved to have quite satisfactory flexing properties at LN_2 temperatures, and are being used for all in-chamber cables.

g. External Wiring Assembly

The external wiring poses no particular problem, and is mentioned here only for completeness. The external cabling is shown schematically in Figure 11.

h. Control

A 386 microprocessor is being built into the STAR system even though the requirements of the Phase 1 demonstration could be satisfied with a far less capable controller. The controls for the Phase 1 demonstration are relatively simple: vertical position commands are given via keyboard input and the motor encoder provides the necessary position feedback. Software limits are incorporated, and are backed up by mechanical limit switches. The pan/tilt unit is run on the same principle. The focal length of the lens system on camera 3 is controlled open-loop by the operator.

Later phases of the program will see more complex control loops incorporated.

STATUS

Table V summarizes the status of each of the assemblies of the STAR system; the present schedule calls for the system to be installed in the 10-ft SS by the end of August, and for the first full-up demonstration of the system by the end of September.

REFERENCES

1. Diner, D. B. "Stereo Viewing System for STAR" JPL IOM 3474-92-059, June 30, 1992

2. Diner, D. B., and D. H. Fender "Human Engineering in Stereoscopic Viewing Devices" JPL Report #D-8186, January 15, 1991

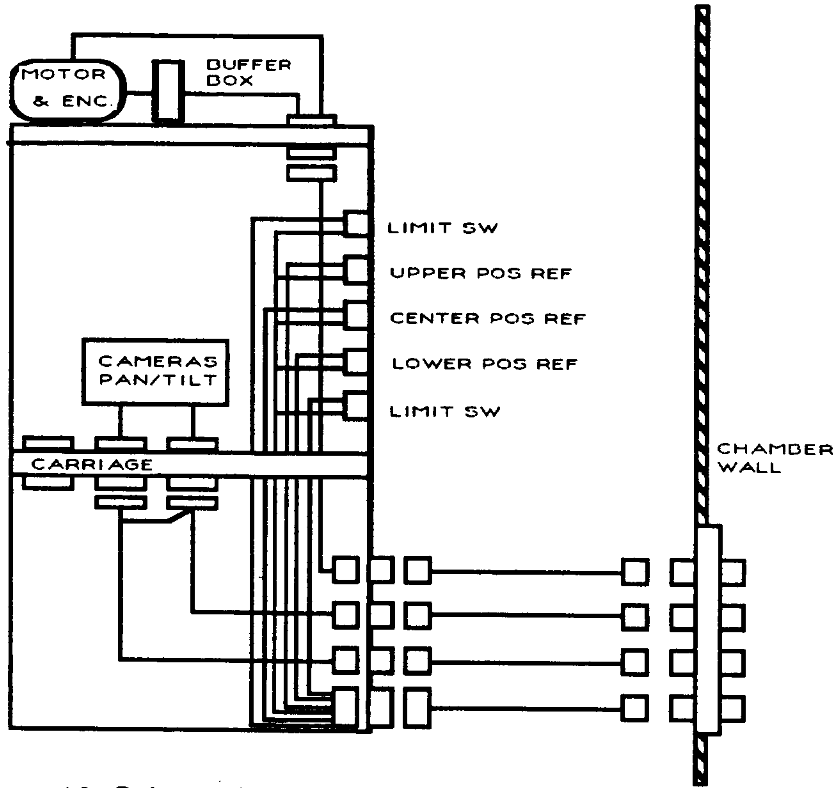

Figure 10. Schematic of the Internal Cabling Assembly

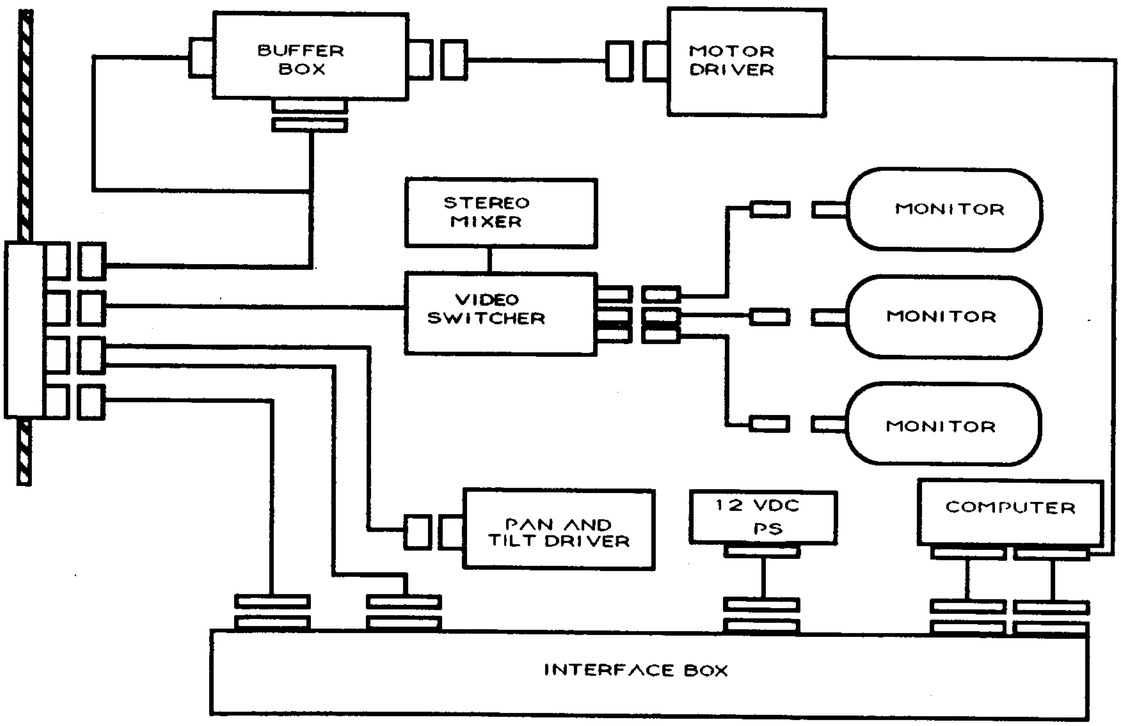

Figure 11. Schematic for the External Cable Configuration

Table V

Status Summary

	Detail Design/ Proc. Spec.	Fabricate Procure	Deliver	Assemble/ Checkout
Drive	Complete	Complete	Complete	Complete
Drive Motor	Complete	Placed	Due Aug 14	
Carriage	Complete	In Process	Due July 31	
Beam	Complete	Complete	Complete	Complete
Pan/Tilt	Complete	Existing		Complete
Cameras	Complete	Placed	Due Aug.3	
Internal Cabling	Complete	In Process	Due Aug 15	
External Cabling	Complete	In Process	Due Sept. 1	
Control Console	In Process		Due Sept. 1	