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Performance of the Satellite Test Assistant Robot in JPL's Space Simulation Facility

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Abstract

An innovative new telerobotic inspection system called STAR (the Satellite Test Assistant Robot) has been developed to assist engineers as they test new spacecraft designs in simulated space environments. STAR operates inside the ultra-cold, high-vacuum, test chambers and provides engineers seated at a remote Operator Control Station (OCS) with high resolution video and infrared (IR) images of the flight articles under test. STAR was successfully proof tested in JPL's 25-ft (7.6-m) Space Simulation Chamber where temperatures ranged from +85 °C to -190 °C and vacuum levels reached $5.1 \cdot 10^{-6}$ torr. STAR's IR Camera was used to thermally map the entire interior of the chamber for the first time. STAR also made several unexpected and important discoveries about the thermal processes occurring within the chamber. Using a calibrated test fixture arrayed with ten sample spacecraft materials, the IR camera was shown to produce highly accurate surface temperature data. This paper outlines STAR's design and reports on significant results from the thermal vacuum chamber test.

Introduction

Before a new spacecraft design is flown in space, it must first undergo severe testing in a simulated space environment where it is exposed to high vacuum, cold temperatures or varying intensities of artificial solar light. These environmental tests are used to establish the spacecraft's flight worthiness.

Conducting these tests can be relatively expensive. Hundreds of thousands of dollars can be invested in a typical two or three day test. Often the test articles are instrumented with several hundred thermocouples, but it is difficult (or impossible) to cover the test article sufficiently to obtain all the data one would like. If anomalies occur during the test or if the article performs in an unexpected manner, the engineers and chamber operators typically have no way of adjusting sensors and have only limited visual access inside the chamber once the test is begun. It can be very costly to stop a test, open the chamber, make adjustments and then restart. Because of the expense involved, it is important that the test data be reliable and complete the first time. In addition, a significant amount of man-hours are needed each year to perform routine chamber calibration and maintenance.

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In 1992, under the sponsorship of NASA Code C (now Code X), engineers in JPL's Robotics and Automation Section and the Environmental Test Chamber Operations Group began a new project to use existing technology and expertise to develop a remotely controlled telerobotic inspection system. The new device would augment and improve existing data collection capabilities and help reduce the costs of performing tests within the environmental test chambers. Significant savings could be obtained if the mobile inspection capabilities of the new device could help prevent even one premature test shutdown. The new device could also help reduce costs by helping chamber operators locate and identify faulty or malfunctioning equipment. This new project is called STAR (the Satellite Test Assistant Robot).

This paper presents an overview of the STAR system design and reports on the successful proof tests conducted in JPL's 25-ft (7.6-m) Space Simulation Chamber.

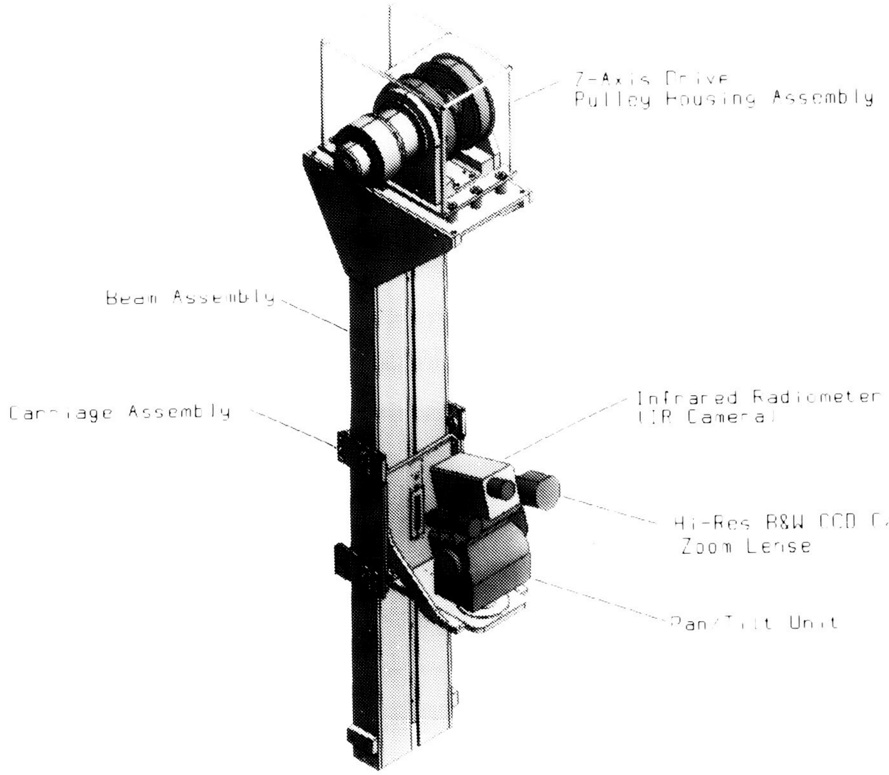

Figure 1. Satellite Test Assistant Robot (STAR) In-Chamber Equipment

The STAR Design

Building anything that can operate in space, or in our case a simulated space environment, is an exceptionally challenging undertaking. And it's not inexpensive. The original design concept, which proved to be quite overly ambitious, called for building of a 25-ft (7.6-m) tall by 25-ft (7.6-m) diameter, heavy lift, clean-room quality robotic gantry system inside JPL's Space Simulation Chamber where temperatures can drop to -190°C. The robotic gantry system was to carry a 3.6-m (12-ft) long, multi-DOF robotic arm and a pan/tilt system with stereo camera capability [1]. Budgetary constraints, as they often do, forced a much needed reality check and the design was subsequently scaled back to satisfy only the most essential needs of the end-user, i.e., the chamber operators and spacecraft test engineers.

The current implementation of STAR consists of a vertical positioning system (the Z-Axis) and a pan/tilt unit that articulate a set of video and IR cameras. The length of the Z-Axis beam can be easily changed, anywhere from 0.6 to 7.6 m (2 to 25 feet) or more, for mounting in a variety of thermal vacuum test chambers. A 2.4-m (8-ft) Z-Axis is shown in Figure 1 and was used during STAR testing in JPL's smaller 10-ft (3-m) Chamber in 1993 [2]. The in-chamber equipment, shown in Figure 1, is remotely controlled from an Operator Control Station (OCS) shown later in Figure 6.

STAR Z-Axis

One of the most significant design challenges in the STAR project was the design of the vertical Z-Axis. How can you get anything to move over large distances, reliably, smoothly, accurately and cleanly at -190°C, and design it economically? As shown in Table 1, we evaluated several design alternatives. The characteristics and design parameters of interest are listed in the column on the left in Table 1. The various candidate drive mechanisms considered are listed across the top . On a scale from 1 to 5, with 1 being the best, an engineering judgment was made as to how well each of the candidate drives met the design criteria. The comparison clearly revealed the best design solution was to use a metal belt design.

After a significant amount of research and consultations with JPL materials experts a choice was made to use a 0.2-mm (0.008 in) thick x 50.8-mm (2 in) wide half-hard 304 stainless steel belt which wraps over a 25.4-cm (10 in) diameter pulley. Of primary concern was brittleness and fatigue strength of the material at LN_2 temperatures. During this time in the design process, we were still expecting the belt drive design would need to lift 136 to 180 kg (300 to 400 lb) of robot arm (this requirement was later changed and greatly reduce during a project de-scope). Because of the catastrophic consequences of a broken drive belt, a redundant two-belt system was designed. Laboratory tensile tests on sample belts and mounting brackets at room temperature revealed that each belt can withstand a 907 kg (2000 lb) load before breaking.

Table I

Comparison of Candidate Drive Mechanisms

MECHANIZATION / CHARACTERISTIC	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 Custom 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 SELECTION

The resulting Z-Axis belt drive design is a relatively inexpensive, easily scaleable, highly reliable, fail-safe, clean-room quality drive mechanism.

The Z-Axis is driven by a 7 N•m (62.5 in•lb) brushless DC motor that is rated to operate in the space-like environment. Connected at the back of the motor shaft is a 24 VDC fail-safe brake that engages whenever power is removed from the system. There is also a 1000 line optical encoder. The Z-Axis motor drives dual 25.4-cm (10 in) diameter pulleys through a 50:1 harmonic drive resulting in a 240 kg (530 lb) lifting capacity.

The carriage assembly was designed with 12 spring-loaded Vespel guide wheels (Figures 2 and 3). The wheels are spring loaded to accommodate the significant dimensional changes caused by the large thermal variations in a typical chamber test.

Even though it is by far the largest individual component in the entire STAR assembly, the Z-Axis beam, by design, is one of the most inexpensive. It's basically just a standard 10 x 30.5 cm (4 x 12 in) aluminum 6061-T6 C-channel beam that has been black anodized (See cross section in Figure 2). As mentioned before, the beam can be cut to any length for mounting in various sizes of chambers.

Another challenging design problem was the electrical cable design for the Z-Axis Carriage. At -190°C, most materials, including copper wires, tend to become quite stiff and do not like to bend. In typical space flight applications, this problem is overcome by pre-warming mechanisms having electrical wires attached to at least -50°C before being actuated. In our design situation, that was not practical since we wished to have the STAR structure blend in with surrounding chamber cold shrouds. Another design consideration was that we wished to have the electrical cable contained within the vertical beam for two reasons: first to avoid snagging the cable on flight hardware as STAR was moved within the chamber, and secondly, the metal structure of the beam would act as a faraday shield to help reduce any electro-magnetic interference (EMI) caused by STAR. EMI pollution in the chamber during a test was to be minimized since it may affect sensitive spacecraft instruments.

These problems were overcome by designing the Z-Axis Carriage cable to be contained within the Z-Axis beam at all times. A special cable was constructed with a unique flat braided weave. The cable attaches inside the beam at the half height point. A length of cable equal to at least half the travel of the carriage is then looped down within the beam, forming a traveling loop. The flat cable weave allows an 28 cm (11 in) diameter, 180° bend in the cable to travel up and down inside the C-channel behind the metal drive belts as the carriage is lifted and lowered.

STAR Pan/Tilt Unit

The pan/tilt unit in STAR is an off-the-shelf product that has been adapted for use in the thermal vacuum test chamber environment. This particular design actually violates most of the design goals we were trying to achieve in the STAR design, i.e. avoiding rubbing contacts points and chain drives that produce contaminates, avoiding the use of AC motors to reduce EMI output, etc. However, it has two major benefits going in its favor. First of all, it has a usage heritage. A pan/tilt unit very similar to the one we selected had been used several times before within the chamber during thermal vacuum operation. The chamber operators were confident and comfortable in using the design. And secondly, it was inexpensive. Our limited design and fabrication budget at the time was the real determining factor that drove us to go with this particular off-the-shelf design (see Figures 4 and 5). The pan/tilt unit cost about $1500. It could of easily cost 10 times that amount to design, build and qualify a better design. In the age of faster-better-cheaper, sometime cost is the determining factor.

The off-the-shelf pan/tilt was modified for use in the thermal vacuum environment by 1) completely disassembling the entire unit, motors and all, 2) removing paint from parts

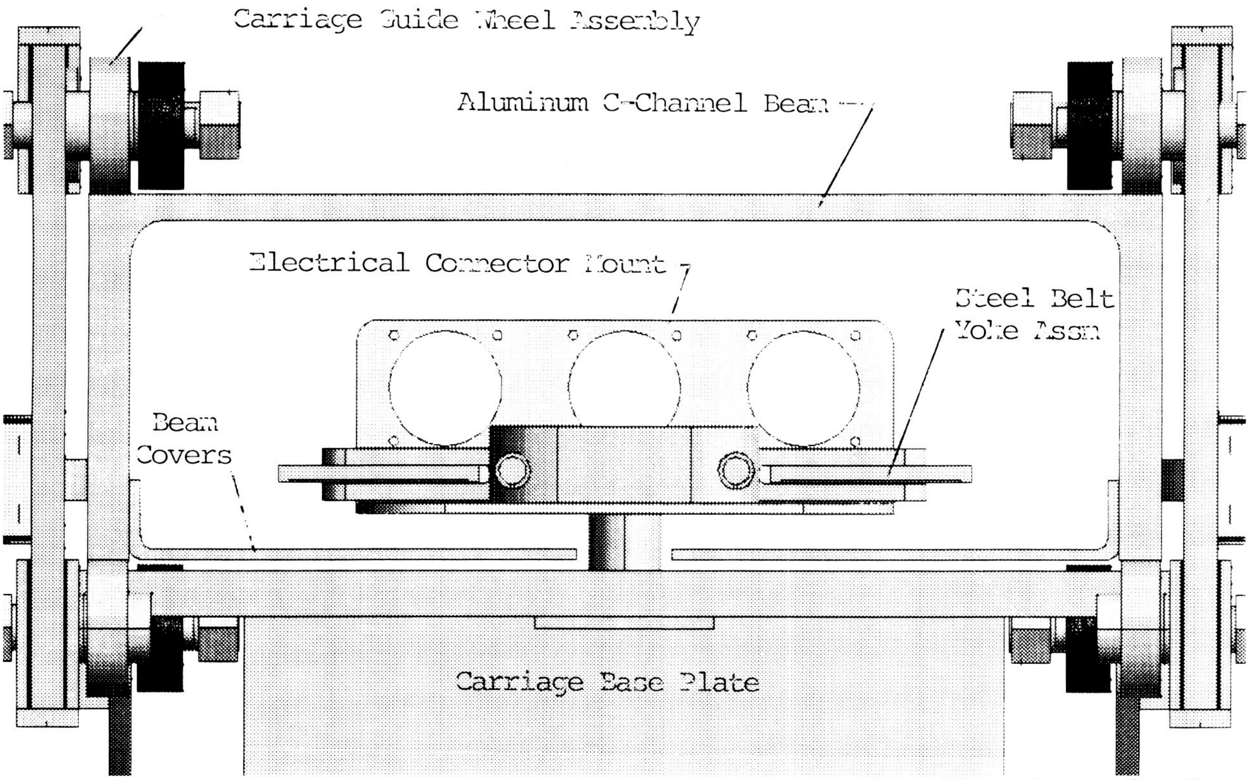

Figure 2. STAR Carriage and Z-Axis Beam Assembly, Top View Cross Section

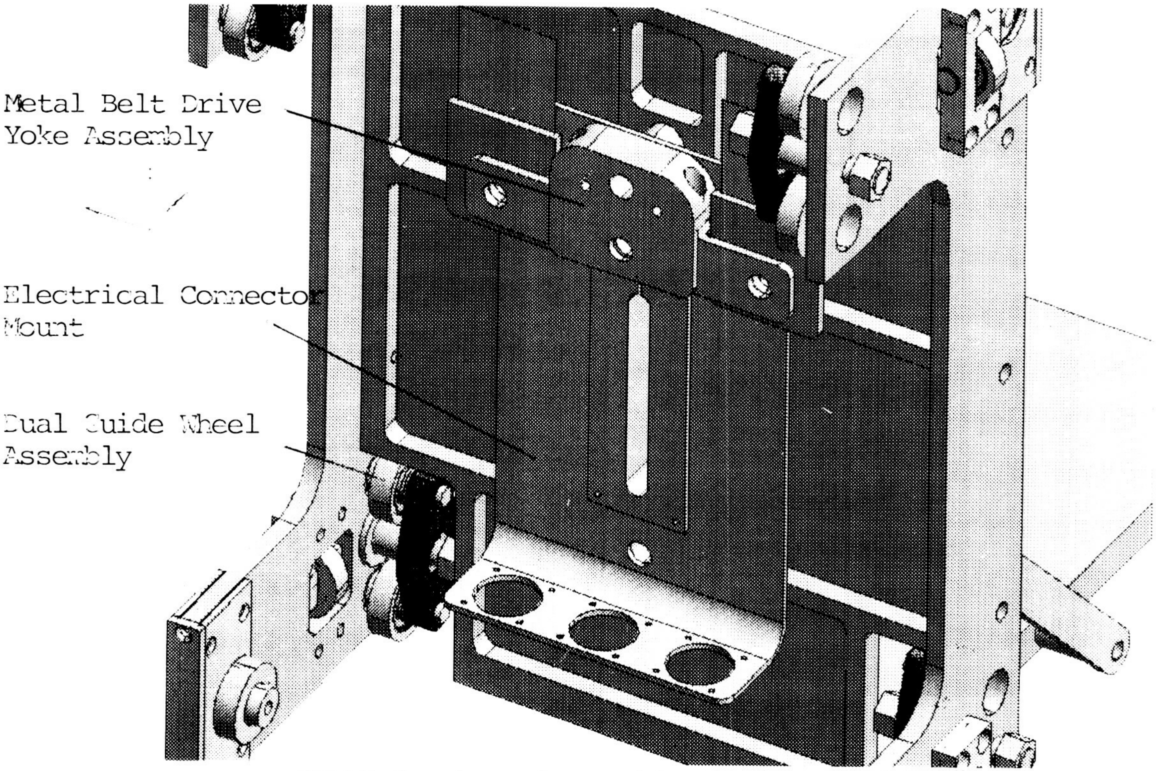

Figure 3. STAR Carriage Assembly, Back Isometric View

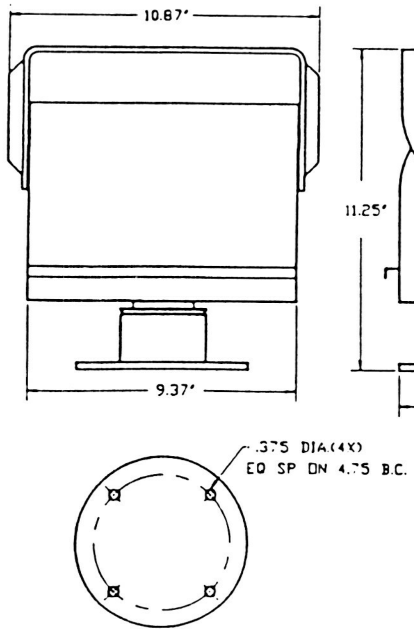

Figure 4 STAR Pan/Tilt Unit, Front, Side and Bottom Views

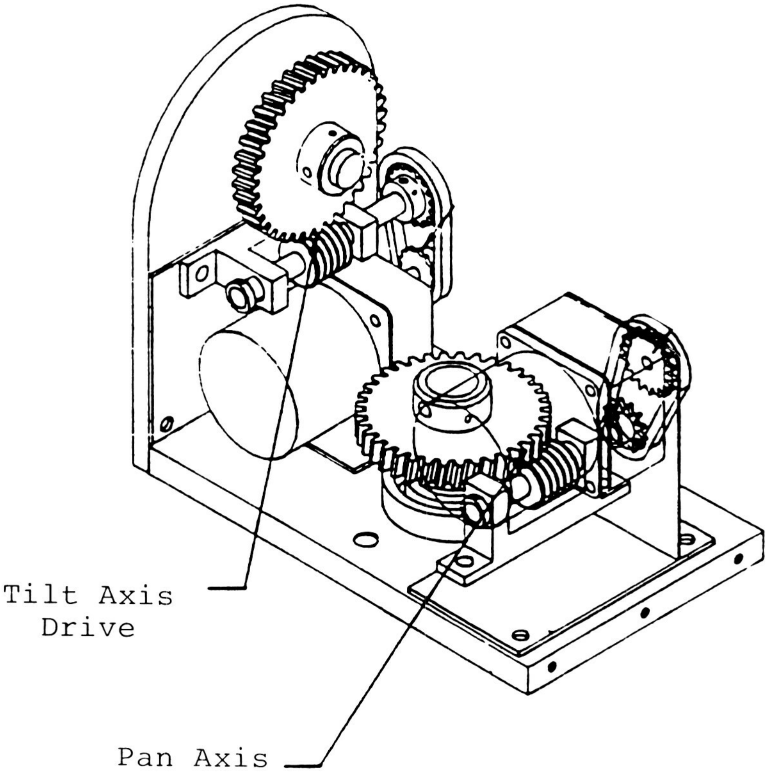

Figure 5 STAR Pan/Tilt Unit, Internal Drive Mechanisms

and anodizing, 3) removing all grease and oils in bearings and gears throughout and recoating the worm drives with a 10% Braycote 600 vapor deposition, 4) removing all electrical wiring and replacing it with flight quality Teflon insulated wire, 5) fabricating a new pan/tilt cover that could be sealed to prevent escape of any particulate contaminates, and 6) baking out (out-gassing) the entire unit in a high temperature, high vacuum, bell jar chamber.

It is pointed out here that the selection of this pan/tilt design, as opposed to designing one from scratch, was a somewhat risky proposition. However, later test results showed that it worked well in a thermal vacuum environment, but it also, surprisingly, was a very clean piece of hardware. The ability to achieve extremely high vacuum levels during bake out indicated that the pan/tilt hardware produced an exceptionally small amount of out-gassing.

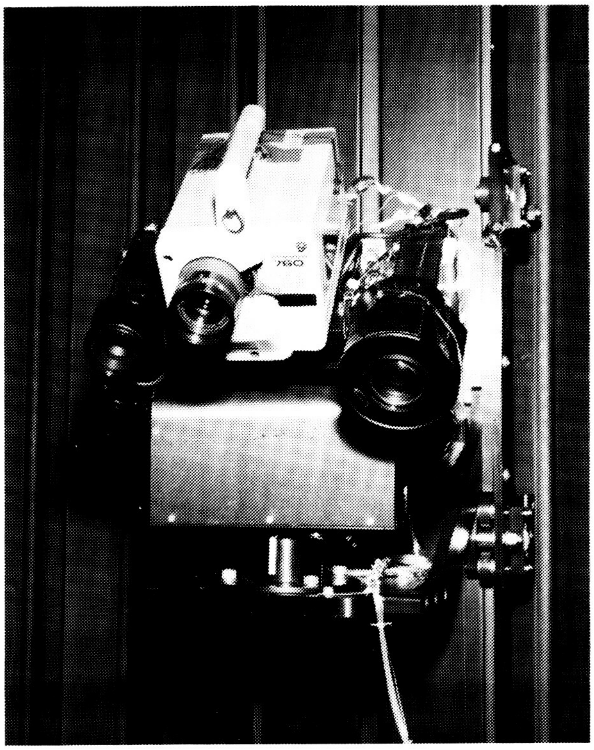

Figure 6 STAR Video & IR Camera Instrument Package & Pan/Tilt Unit

STAR Instruments

Of the technological contributions made by STAR, one of the most important is the introduction of IR imaging technology into the thermal vacuum test chamber environment. Engineers can now perform non-contact temperature measurements on all exterior spacecraft surfaces.

As mentioned previously, the STAR instrument platform, shown in Figure 6, consists of two high-resolution vacuum-rated Pulnix CCD video cameras fitted with fixed and zoom lenses. In addition, it has an Inframetrics Model 760 Infrared Radiometer (IR Camera) and computer-controlled lighting. A series of heating elements and thermostats were mounted to these instruments to maintain vendor-specified operating temperature ranges. The front half of the camera assembly was covered by a thermal blanket to protect from direct solar light irradiation.

STAR Operator Control Station (OCS)

An operator seated at STAR's OCS outside the chamber can remotely control the instrument platform inside the chamber by using a computer touch screen display and graphical user interface (GUI). Operators can control the elevation and orientation of STAR's instrument platform and make adjustments to camera settings, capture and manipulate images, adjust lighting conditions and perform system diagnostics, etc.

STAR's OCS is the double rack console shown in the left forefront of Figure 7. It was a new development for FY'94 and serves as the primary user interface for system operation. The main OCS control computer is a standard NEC 486-PC running Windows. It incorporates a touch screen display from Micro-Touch and a new LabView-based GUI that provides easy and simple access to all of STAR's functions via the touch screen. The OCS control computer is equipped with Precision MicroControls' DCX PC100 servo control modules and analog and digital I/O. A three-channel video board from Win/TV provides on-screen video image capture and processing. The OCS also has two high-quality video monitors and a built-in VCR. The OCS rack also houses a system I/O Interface Box with manual control switches, a Power Distribution Box, and the motor amplifier that powers STAR's vertical Z-Axis.

Putting STAR to the Test

On December 20, 1994, STAR successfully completed a critical thermal/vacuum qualification test in JPL's 25-ft (7.6-m) Space Simulation Facility where chamber temperatures ranged from +85 °C to -190 °C and vacuum levels reached 5.1×10^{-6} torr. During the test, STAR performed extremely well and provided much new information about the dynamic processes within the thermal vacuum test chamber.

The overall objectives of this test were two-fold: 1) functionally test the STAR hardware in the space simulator and 2) determine the accuracy of the IR Camera. The primary motivation for conducting this test was to further validate STAR's functionality and performance in harsh thermal/vacuum environments. Last year, much of the STAR's in-chamber hardware underwent two previous thermal/vacuum tests conducted in JPL's smaller 10-ft (3-m) Chamber [2]. Testing in the 25-ft (7.6-m) Chamber qualified the STAR hardware operations in that chamber and it also provides additional levels of confidence and experience operating the equipment in harsh environments.

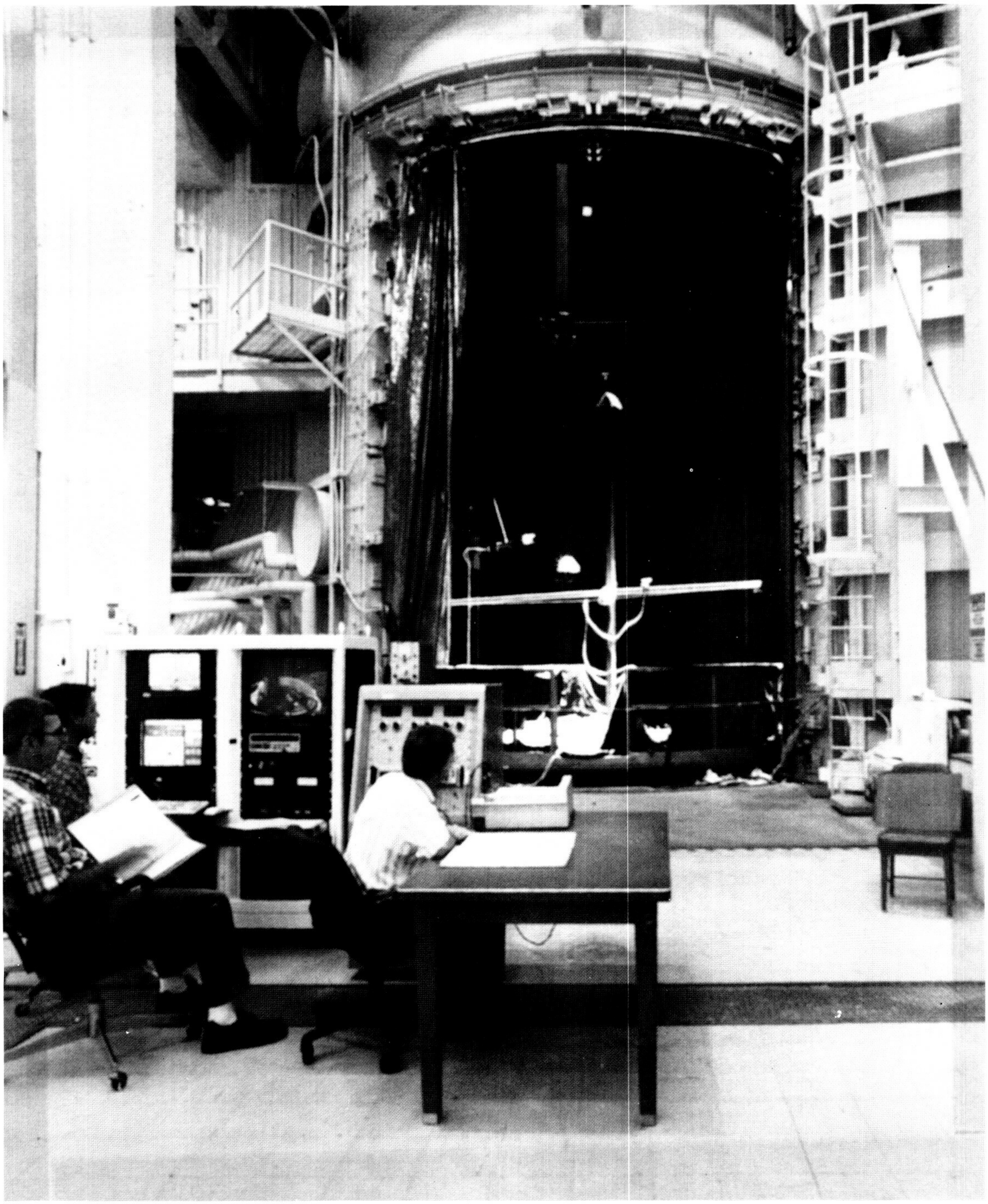

Figure 7 STAR during installation in JPL's 25-ft (7.6 m) Space Simulation Facility

Of primary interest in this test was the performance of several off-the-shelf, non-flight, non-vacuum rated components contained in STAR's mechanical and electrical subsystems, of particular note are the Inframetrics IR Camera, Cosmicar fixed and zoom lenses, and the Pelco pan/tilt unit. These items were modified or adapted for use in the harsh thermal/vacuum environment [3]. Inclusion of these items within the STAR system represented a significant known risk taken in order to meet cost and schedule requirements. Their inclusion also marked a significant variation from traditional hardware design and development practice resulting in a far more inexpensive end product. During the test, we focused much of our attention on these critical items.

The STAR IR Camera was shown to be highly accurate at measuring surface temperatures across a wide variety of sample spacecraft materials. Even on difficult, low emissivity materials the IR Camera's thermal measurements differed from those measured by conventional thermocouple networks by only 0.5 °C. Part of the test was to investigate what is the coldest temperature range the IR Camera can resolve. Surprisingly we were able to image temperatures to about -70 °C with only 4 to 5 °C discrepancy from traditional thermocouple measurements.

During this test STAR was instrumental in making several significant new discoveries about thermal dynamic processes within the 25-ft (7.6-m) Space Simulation Facility. These discoveries include:

1. For the first time chamber operators were able to find distinct blockages in several individual chamber shroud radiator tubes. Figure 8 is a captured video image showing the lower portion of the 25-ft (7.6-m) Chamber's door cooling shroud. Figure 9 is an image from the IR Camera showing 4 blocked shroud cooling tubes. The original IR image is in vivid color but in this black and white image the blocked tubes show up as dark gray.

2. STAR was also able to pin-point and quantify several chamber hot spots.

3. STAR's vivid thermal images clearly showed a more than 70°C lag between the chamber's door shroud and the rest of the chamber.

4. STAR's IR Camera also found that a surprisingly large thermal gradients existed across a commonly used heat exchanger plate.

Results and Conclusions

The STAR hardware and software performed extremely well throughout the test with only a few minor glitches, for example, during the access of an IR Camera GUI sub-menu item the main control computer hung which required a system reboot. The sub-menu software interface will be modified in the future. The functionality of all systems and subsystems were randomly checked about every 20 minutes and 18 hours of

Figure 8 Captured Video Image of Chamber Door Shroud

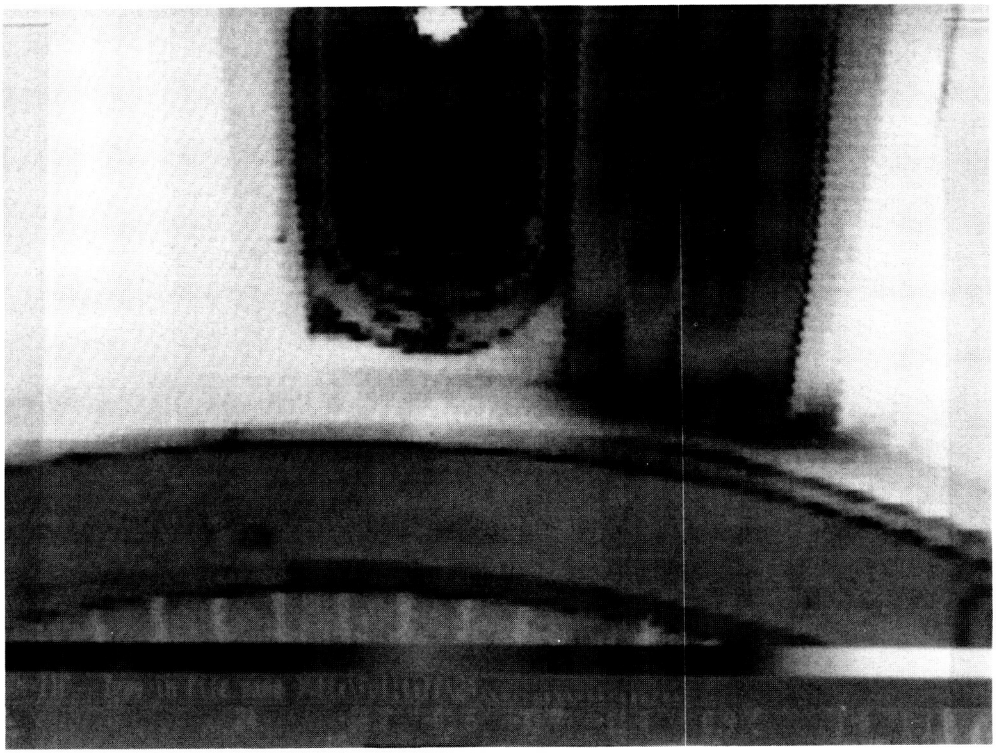

Figure 9 IR Camera Image of Chamber Door Shroud Revealing Blocked Tubes

video tape were recorded of all images displayed to STAR's main OCS monitor. There were also 24 IR Camera images were captured and saved to diskette.

Thermal engineers and chamber operators at JPL participated in the test and seem to be very enthusiastic about using STAR in future spacecraft thermal/vacuum environmental tests. STAR allows, for the first time, non-contact measurements to be made in the harsh high vacuum, ultra-cold temperature test chamber environment. This opens up a whole new wayof testing spacecraft at JPL and will be extremely valuable when performing tests on difficult surfaces to instrument with traditional thermocouple techniques such as on antennas, solar panels, radiators, optical surfaces, and moving targets such as rovers and mechanism deployments.

Using STAR's IR Camera, engineers can now thermally map the external surfaces of a spacecraft. The high-resolution video cameras allow detail inspection and documentation of the spacecraft as it is being tested.

STAR's most significant contribution may be that it provides engineers with a means of addressing unforeseen anomalies that often occur during the complicated spacecraft testing process. Once a test is underway, it is very expensive to stop, open the chamber, and make adjustments to sensors or equipment.

STAR was also designed to aid in the calibration and maintenance of the test chambers and the results from this initial test in the 25-ft (7.6-m) Space Simulation Chamber produced an astonishing amount of new information as to how the thermal components within the chamber perform.

Acknowledgments

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