UTILIZATION OF THE SATELLITE TEST ASSISTANT ROBOT (STAR) FOR VISUAL AND THERMAL ANALYSIS OF ARTICLES IN THE THERMAL VACUUM TEST ENVIRONMENT

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ABSTRACT

An innovative new telerobotic inspection system called STAR has been developed to assist engineers in the visual and thermal analysis of flight hardware being tested in a simulated space environment. STAR, operating in a thermal vacuum chamber, provides high resolution black and white (B&W) video and infrared (IR) images of test articles. Viewing angles may be changed using STAR's z-axis (up and down) as well as its pan and tilt movement capabilities. STAR's movement is controlled by the operator at a remote computer console which includes a graphical user interface actuated by either touchscreen or mouse click. Two monitors provide viewing of video and IR images simultaneousl y and a video tape recorder provides the ability to record either video or IR images in real time. The STAR development was begun in 1991 and was completed in late 1994. The STAR hardware was proof-tested in JPL's 25-ft Space Simulator (SS) in temperatures from 60°C to 190°C and at 10^{-6} torr vacuum. This paper describes the architecture of the STAR mechanical and contr 01 systems and discusses some uses of STAR to date.
Keywords: STAR, Space Simulation, 1 R Camera

INTRODUCTION

The first use of stationary B&W video cameras at JPL was in the spring of 1989 when three vacuum rated Pulnix video cameras were procured and mounted in JPL's 25-ft SS to provide images during a satellite thermal vacuum test. Although the cameras performed well during the test, the fixed location of the cameras rnadc viewing of the test article less than exciting. Everyone wished that the cameras could be moved to different viewing angles during the test. In the summer of 1991, the Telerobotics Group at JPL issued a request for concepts where robotics technology might be applied productively. in response to that request, the author conceived the idea for the development of STAR, a telerobotic imaging system that can be operated in a cold vacuum environment. Working with the Telerobotics Group, a proposal for a robotics develop!~eti.[~r.eject was prepared and sent to NASA, and was subsequently funded. Development activities began in the fall of 1991.

The development of S1 AR was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Designing mechanical equipment for operation inside a thermal vacuum chamber used for spacecraft testing involves design considerations not normally encountered in robotics work. The foremost consideration is chamber cleanliness -- the mechanical parts may not be lubricated with any compound nor be painted with any material that will contaminate the chamber. Also, the moving parts must be capable of withstanding temperatures from -190°C to +140°C. Cables must be vacuum rated and must maintain their flexibility at very cold temperatures. Finally, motors, switches and drive train components must all be vacuum rated and must be able to withstand the cold space temperatures.

The Telerobotics group took these design criteria and, during FY92, produced a working robotics system that provided both monoscopic and stereoscopic imaging of test articles using three Pulnix B&W video cameras. This system consisted of a pulley housing assembly with a vacuum rated drive motor, a carriage assembly with spring-loaded wheels to travel vibration-free on the z-axis of an aluminum beam, a pan-tilt unit mounted on the carriage assembly, three cameras (one with a zoom lens) mounted to the pan-tilt unit, a remote control station with monitors anti a stereoscopic viewing headset to view the test article images.

In FY93, the STAR team continued the development of the computer control console and added an IR camera to the imaging system. Inframetrics, Inc., provided a Model 760 IR Imaging Radiometer to JPL to test the feasibility of operating an IR camera in a thermal vacuum environment. In September 1993, a full performance test was conducted with the STAR system mounted inside one of JPL's thermal vacuum chambers. This test included two Pulnix B& W video cameras (one with zoom lens) and the Model 76011< camera lent to us by Inframetrics for this test. The STAR hardware and all camera systems performed flawlessly yielding excellent and useful images of the thermal response of an engineering model of an element of the Cassini spacecraft power system.

In FY94, the STAR t cam focused on improvement of the remote control system and on preparation of the STAR hardware for a test in JPL's 25-ft SS. A controlled copper base plate to simulate the temperature of the exposed petal on which the Rover is mounted (the base plate closely follows the Mars ground temperature); 2) a temperature controlled sky plate to simulate the diurnal sky temperature; 3) a wind generating machine to simulate wind at 6 m/see and 12m/see; and, 4) a temperature controlled compensator plate to assist in controlling the temperature of the gas being drawn through the wind machine and blown towards the Rover-EM. Figure 3 schematically illustrates the test fixture. Figure 4 is a close-up photo of the test fixture with the Rover mounted in place. Details of the wind machine drive linkage are described below and are illustrated in Figure 5. A temperature controlled chamber wail and floor shroud system served to condition the 8 torr GN2 in the chamber to Mars-like temperatures.

WIND MACHINE DESCRIPTION

Creating wind in an 8 torr environment was a challenging undertaking. A motor-driven fan was selected as the mechanism to generate the wind. An 8-blade, 762 mm (30") diameter stainless steel (SS) fan was driven by a three phase, 8-pole carbon brush, 5 Hp dc motor with a 31.75 mm (1.?!,') S5 shaft. This motor was selected primarily because it was readily available at no cost, A magnetic sensor measured shaft r-pm and a constant speed logic circuit was used to control motor speed up to 1600 rpm. To protect the motor from the cold temperatures and the low pressures of the simulated Mars environment, it was necessary to mount the motor inside a sealed canister [304.8 mm (12") ID, 762 mm (30") long, with 381 mm (15") OD flanges on each end]. The enclosed motor was cooled with a temperature-controlled GN2 gas stream fed through a 12.7 mm (0.5") SS flexhose directly into the motor frame then vented out the canister to atmosphere.

The motor drive linkage included a SS transition [31.75 mm/19.05 mm (1,25"/0.75"), a 19.05 mm (0.75") standard brass coupling, a 19.05 mm (0.75") SS water-cooled Ferrofluidics rotary seal, and a SS 19.05 mm/31.75 mm (0.75 "/1 .25") transition which linked directly to the fan hub. Linkages were keyed and the keys on the transitions were able to be tightened in place with a pair of set screws. The coupling also had one set screw which locked the coupling to the shaft. Linkage details are shown in Figure 5.

To ensure vibration-free operation, the canister was bolted securely to a 381 mm (15") OD, 24-hole flange which was welded to 152.4 mm (6") wide, 12.7 mm (0.5") thick aluminum crossbars and centered at the horizontal centerline of the upstream side of a rigid structural frame [1650 mm (65") H x 1752 mm (69") W x 2032 mm (W") L] fabricated from 101.6 mm (4") square aluminum bar stock. The fan was enclosed in a 813 mm (32") diameter SS sheetmetal housing which was swaged down to a 559 mm (22") diameter at the wind discharge plane. A 559 mm (22") diameter, 12.7 mm (0.5") thick sheet of SS honeycomb with 6.35 mm (0.?5") holes was attached at the discharge plane to direct the wind uniformly towards the Rover-EM. A conical wind diffuser [838 mm (33") base diameter, 432 mm (17") long] was installed at the downstream end of the structural frame to distribute the circulating gases evenly and to minimize the possibility of back-flow buffeting of the wind against the Rover-EM. The Rover-EM was mounted on a tmnperature-controlled copper base plate and was centered in-line with the wind discharge plane facing the wind. A 2946 mm (9'-8") diameter mylar covered disk barrier frame was mounted above the structural frame to help keep the circulating gas contained in the lower portion of the vacuum chamber. Finally, a fan intake cone [686 mm (27") diameter swaged to 381 mm (15") diameter) was installed around the canister to help smooth and direct the intake gas flow stream to the the fan.

The wind speed calibration was done using a hot-wire anemometer which was an engineering model of the Mars Pathfinder Wind Sensor (ASI/MEI). Two reference plates (one gold foil surface and one black paint surface) were installed as a back-up to the hot-wire anemometer to provide a "sanity check" of the actual chamber conditions as well as to help with the evaluation of the heat transfer correlation calibrations. The reference plates were mounted above the rover solar panels, the gold plate followed by the black plate (see Figure 4).

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The Rover-EM test was fraught with challenge. At almost every step in the test plan, the operators were faced with problems that required rapid remedial action. Equipment failures coupled with trial and error operator judgments made this test an unforgettable experience. We learned that creating a simulation of a Martian surface environment is mow difficult than one might imagine.

The test began on the morning of 10/22/95. The initial attempt at evacuation of the chamber with the axial compressor failed because at the onset of pumpdown, the primary chamber door o-ring was not seated properly. Four hours later, after reseating this o-ring, the pumpdown was started again but the chamber pressure leveled at about 4 x 10^{-2} torr indicating a leak. A small leak was found at graphical user interface for operating the various STAR drive functions was developed using Labview software and touchscreen actuation. Also, an Inframetrics Model 760 IR camera was procured and readied for use in the thermal vacuum chamber. In December 1994, a full system functional performance test was conducted in the 25-ft Space Simulator with very successful results.

In October 1995, the IR camera portion of the STAR hardware was mounted inside JPL's 10-ft SS and was successfully used to image the Mars Rover engineering model during its thermal character-ization test. in April and June of 1996, STAR will be used to image Rover movement and Lander thermal response during the Mars Pathfinder thermal vacuum tests in the 25-ft SS. The various systems of STAR are described in more detail in the following text. Figures 1 through 5 illustrate STAR's mech-anical details.

STAR Z-AXIS

The STAR z-axis motion design was one of the most significant challenges of the STAR project. After extensive research in evaluating various drive mechanisms, a design choice was made to use a 0.2 mm (0.008 inch) thick x 50.8 mm inch) wide half-hard stainless steel belt wrapping over a 2.54 mm (10 inch) diameter pulley. Laboratory tests of the belt showed that this belt could with-stand a 908 kg (2000 lb) load before breaking. Because a belt breakage could have catastrophic consequences, a two belt system was designed so that each of the belts alone could take the maxi-mum load of the STAR carriage assembly.

The z-axis motion is provided by a 7 Nm (62.5 in-lb), brushless DC motor that is rated to operate in cold vacuum conditions. A 24 vDC fail-safe brake that engages whenever the drive motor power is turned off, is connected to the back of the drive shaft. The z-axis motor drives dual in-line 254 mm (10 inch) pulleys through a 50:1 harmonic drive yielding a 240 kg (530 lb) lifting capability.

The carriage assembly was designed to be as vibration-free as possible. Twelve spring-loaded Vespel guide wheels serve to keep the carriage assembly closely coupled with the support beam and to accommodate the dimensional variations caused by thermal expansion and contraction over the wide temperature range of operation.

The z-axis beam is a standard 102 mm x 305 mm (4 x 12 inch) aluminum 6061-T6 C-channel beam that has been black anodized. By using the appropriate length beam of the same specification, STAR can be mounted in chambers of various sizes.

The carriage assembly cargo, the pan-tilt unit and the cameras receive power and control signals through a custom-built cable of flight rated wires configured in a flat braided weave. This config-uration allows the cable to be flexible even at low temperatures. The cable is housed inside the C-channel, is attached at the half-height point on the beam and loops down within the beam. The flat cable weave allows a 280 mm (11 inch) dia-meter, 180° bend in the cable as it travels up and down the C-channel beam behind the stainless steel drive belts.

STAR PAN-TILT UNIT

The pan-tilt unit used in STAR was an off-the-shelf commercial product that was modified for use in the thermal vacuum environment. The modifica-tions included 1) completely disassembling the unit, 2) removing paint and anodizing from metal parts, 3) cleaning out all lubricating greases and oils from bearings and gears and replacing them with a 10% Braycote 600 vapor deposition coating, 4) replacing all wiring with flight-quality Teflon-insulated wiring, 5) fabricating a new pan-tilt unit cover that could be sealed to prevent the escape of particulate contaminants, and 6) baking the entire assembly at 100 °C in vacuum to outgas residual contaminants.

STAR INSTRUMENTS

The instrument platform mounted on the pan-tilt unit consists of two high resolution vacuum-rated Pulnix CCD B&W video cameras, one fitted with a zoom lens, the other with a fixed focal length lens, and an Inframetrics Model 760 infrared Imaging Radiometer (IR camera). Heating elements were attached to these cameras and were wired to thermostats to maintain vendor specified operating temperatures during cold temperature excursions. Also, four computer-controlled lights were mounted near the cameras to provide illumination of test articles as needed. The camera assembly was covered by a thermal blanket to protect it from direct solar irradiation as well as to insulate it from the cold chamber walls.

STAR OPERATOR CONTROL STATION (OCS)

STAR is controlled at the OCS located outside the chamber. The OCS is a double racked console equipped with a standard 486-PC running on a Windows 3.1 operating system, a 356 mm (14 inch) color monitor with a Micro-Touch touch screen display, and a Labview-based graphical user interface. The OCS control computer contains Precision MicroControls' DCX PC100 servo control modules and analog and digital 1/0 ports. A three-channel video board from Win/TV provides on-screen video image capture and processing. The OCS has two high quality video monitors and a built-in VCR for recording the output from the IR camera or either of the two B&W cameras. The OCS rack also houses a system I/O Interface Box which includes manual control switches for pan, tilt, zoom and z-axis position, a power distribution box and the motor amplifier that powers STAR's z-axis drive motor. At the OCS, an operator is able to control the elevation and orientation of STAR's instrument platform and to make adjustments to camera settings, to capture images, to adjust lighting and to perform system checks/diagnostic...

STAR UTILIZATION TO DATE

The STAR system has been used several times since its' installation. First, during the mapping of the uniformity of the solar beam intensity for JPL's refurbished solar simulation system in the 25-ft SS, STAR was used to monitor the chamber floor and mapping equipment for hot spots. One observation made by 1 R camera was that the cable guards which were shielding the mapping equipment cables from the direct light were getting very hot during periods of illumination. This observation led to the removal of the cable guards to prevent overheating of the wiring. Second, during the final functional performance test of STAR in a full cold vacuum environment, the IR camera revealed that four of the finned aluminum shroud pipelines were being cooled and heated slower than were adjacent lines. Cooling and heating of the personnel door also lagged the adjacent chamber shrouds. These findings identified chamber thermal anomalies that need to be considered during thermal analysis of test results.

In October of 1995, the IR camera was used to image the thermal response of the Mars Rover to simulated Martian environmental conditions. With the use of STAR, variations of cooling rates on the Rover surfaces could be seen in real time.

In April and June of 1996, STAR will be used to observe the Mars Pathfinder spacecraft while it is being tested in both simulated space conditions and simulated Martian surface environment conditions

FUTURE ENHANCEMENTS/APPLICATIONS

A planned near term future enhancement to the STAR system is to provide the capability to broadcast live or recorded video or IR images directly to guest investigators via the Internet by utilizing Cornell University's CUCEEME software. This capability would allow engineers to witness spacecraft tests from locations on-lab at JPL or world wide. Using the NASA television broadcast model, a copy of the STAR image output would be fed into a CUCEEME reflector and from there onto the Internet. Access to the images could then be accessed on Macintoshes or Windows-based workstations by simply connecting to the Space Simulator reflector site. We plan to implement this capability for use during the upcoming thermal vacuum testing of the Mars Pathfinder spacecraft in JPL's 25-ft SS.

The STAR hardware has been proven to operate effectively in a cold vacuum environment. This capability allows visual and thermal analysis of spacecraft while being tested in thermal vacuum chambers. However, an extension of this technology goes beyond terrestrial-based thermal vacuum chambers. Space-based applications of STAR-like systems may prove beneficial for many missions. It can be envisioned that a STAR-like system could be mounted along the longitudinal axis of the shuttle's payload bay to image temperature transitions of payload articles. Also, a STAR system may be useful for space-side applications for the International Space Station Alpha for thermal or visual analysis of external surfaces and components,

SUMMARY

The STAR system is a valuable new tool for use in thermal vacuum test chambers. Thermal imaging of test article surfaces with the IR camera from a variety of viewpoints enhances the the ability to analyze thermal characteristics of test articles in space simulation chambers. Also, the video cameras provide a method to visually inspect and image-document test articles in cold vacuum conditions. Further, the technology of this type of imaging system can be extended to applications in actual space environments. The team members who conceived, designed, fabricated, implemented and tested STAR are excited by STAR's excellent performance and are interested in encouraging widespread use of this technology within the space community. We invite serious inquiries which could result in the development of STAR-like robotic devices for space applications.

ACKNOWLEDGEMENTS

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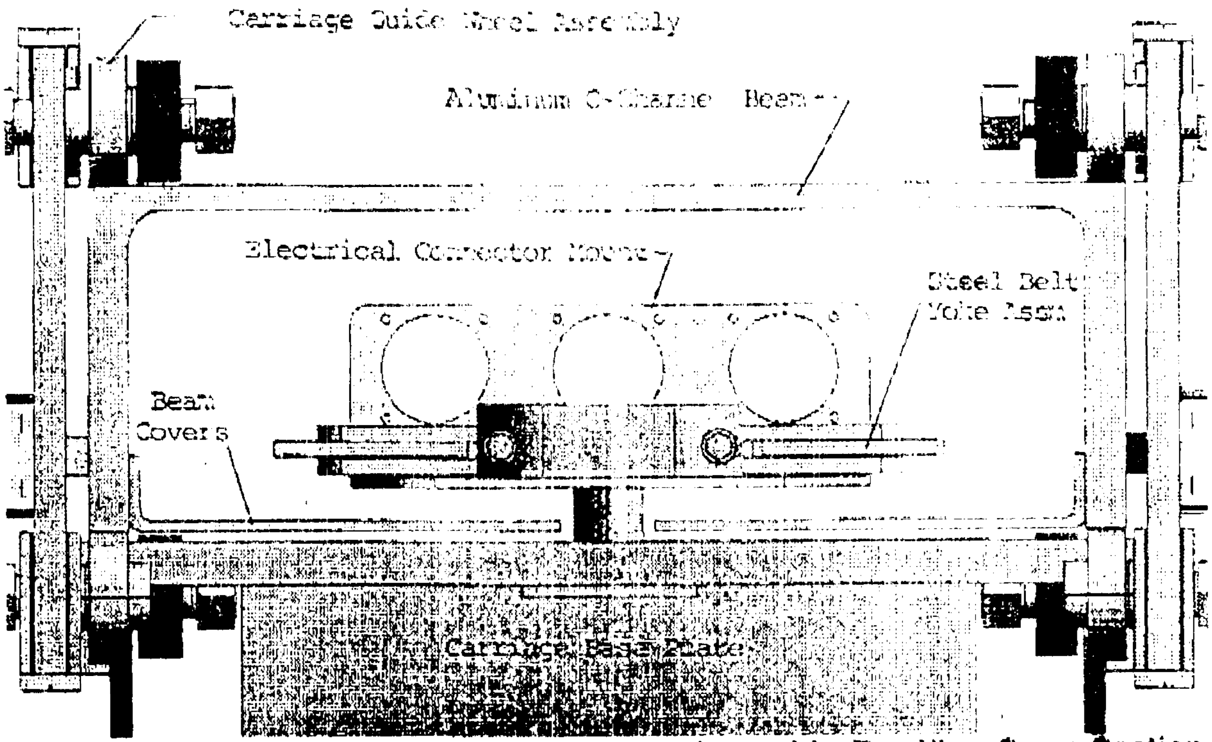

Figure 2. STAR Carriage and Z-Axis Beam Assembly, Top View Cross Section

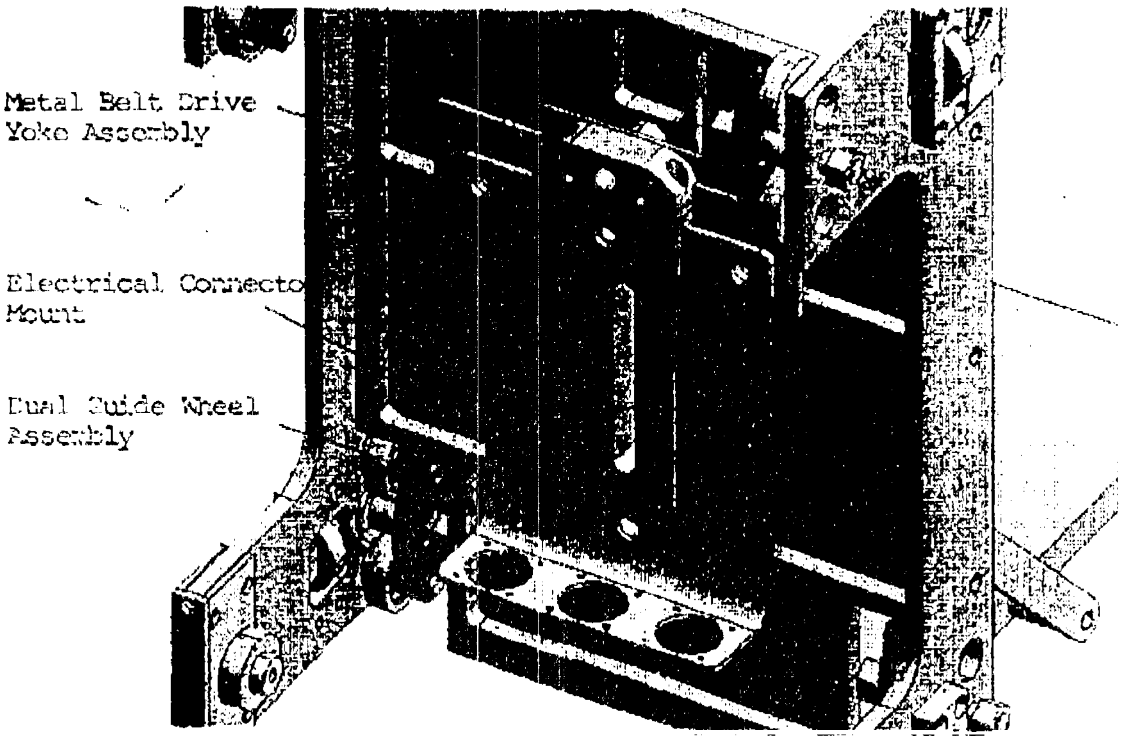

Figure 3. STAR Carriage Assembly, Back Isometric View

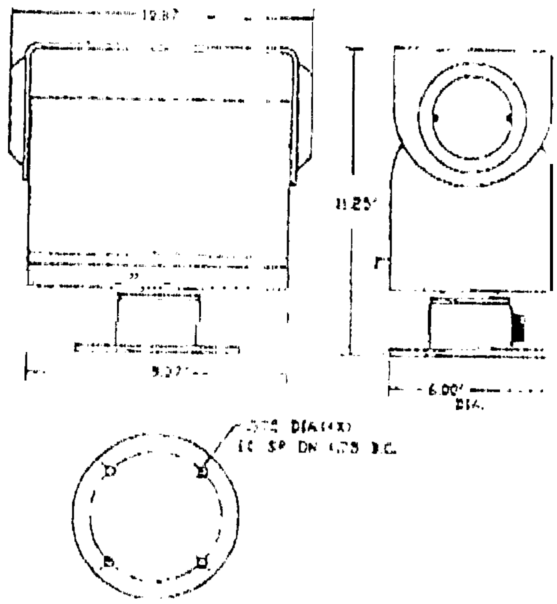

Figure 4 **STAR Pan/Tilt** Unit, Front, **Side and Bottom Views**

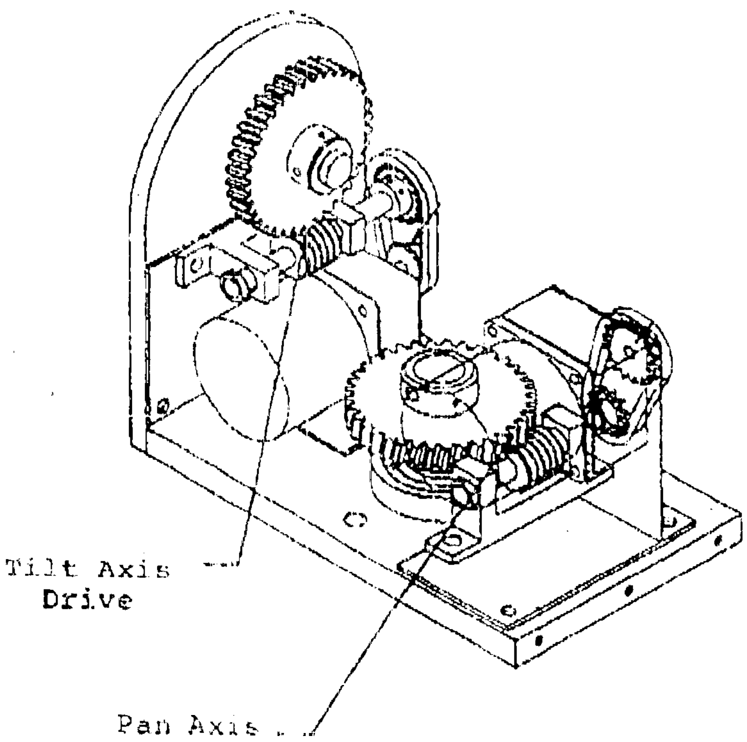

Figure 5 **STAR** Pan/Tilt Unit, **Internal Drive** Mechanisms