The Development of high-precision hexapod actuators for the Hobby-Eberly Telescope[†] Wide Field Upgrade

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ABSTRACT

Hexapods are finding increased use in telescope applications for positioning large payloads. Engineers from The University of Texas at Austin have been working with engineers from ADS International to develop large, high force, highly precise and controllable hexapod actuators for use on the Wide Field Upgrade (WFU) as part of the Hobby Eberly Telescope Dark Energy Experiment (HETDEX)[‡]. These actuators are installed in a hexapod arrangement, supporting the 3000+ kg instrument payload which includes the Wide Field Corrector (WFC), support structure, and other optical/electronic components. In addition to force capability, the actuators need to meet the tracking speed (pointing) requirements for accuracy and the slewing speed (rewind) requirements, allowing as many observations in one night as possible. The hexapod actuator stroke (retraction and extension) was very closely monitored during the design phase to make sure all of the science requirements could be met, while minimizing the risk of damaging the WFC optical hardware in the unlikely event of a hexapod actuator or controller failure. This paper discusses the design trade-offs between stiffness, safety, back-drivability, accuracy, and leading to selection of the motor, high ratio worm gear, roller screw, coupling, end mounts, and other key components.

Keywords: HETDEX, HET, CEM, hexapod, actuator, precision, pointing, tracker

[†]The Hobby-Eberly Telescope is operated by McDonald Observatory on behalf of the University of Texas at Austin, the Pennsylvania State University, Stanford University, Ludwig-Maximillians-Universität München,and Georg-August-Universität, Göttingen

[‡]http://hetdex.org/

1. INTRODUCTION

The Hobby-Eberly Telescope (HET) in Figure 1, located in the Davis Mountain Range at The University of Texas' McDonald Observatory, has been conducting science operations since October, 1999[1]. The HET is a modified Arecibo-style telescope, with a 9.2-meter segmented primary mirror tilted at a fixed zenith angle of 35°[2]. The star tracker mounts above the primary mirror at prime focus on the upper-most portion of the telescope, termed the upper hexagon or "upper hex". Corrector optics mounted to the tracker are positioned via two linear drive systems and a six degree of freedom (DOF) hexapod maintaining the instruments' optical axis normal to and on the focal sphere of the primary mirror.

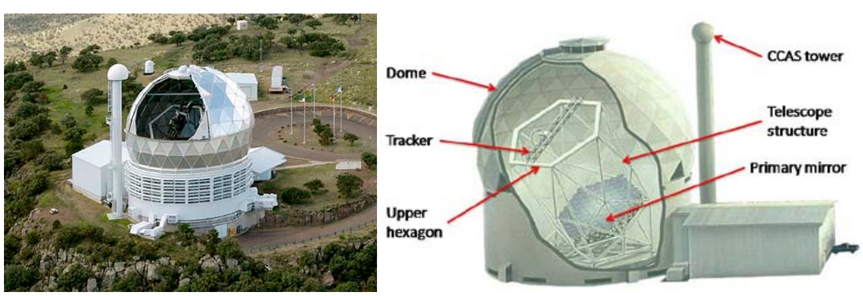

Figure 1. The figure on the left shows an aerial view of the HET with the shutter open. The computer rendering on the right reveals the major components of the telescope.

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The Hobby-Eberly Telescope is currently undergoing a major redesign effort in preparation for the Dark Energy Experiment[3,4]. The upgrade, referred to as HETDEX, involves replacing the current star tracker[5] along with its drive systems. The catalyst for the replacement of this hardware is the wide field upgrade to the corrector optics. Replacing the current spherical aberration corrector (SAC) with the wide field corrector[6] will increase the HET field of view from 4' to 22'. In addition, the current science instruments[7] will be supplemented with the Visible Integral-field Replicable Unit Spectrograph[8,9,10] (VIRUS). These changes will allow the telescope to conduct the largest survey of distant galaxies ever attempted.

A six axis hexapod is an integral part of the Hobby Eberly Telescope (HET) positioning system. In the HET telescope design, the hexapod is used to locate the Primary Focus Instrument Package (PFIP) optical hardware to the appropriate location relative to the primary mirror. The hexapod actuators are located at the mechanical connection between the tracker bridge (x-y motion) and a passive hexapod structure which supports the PFIP optical hardware. The actuators have been designed to meet a broad number of performance requirements, which include overall length, travel, stiffness, end joint rotation, heat generation, slewing/tracking speed and acceleration, and most importantly, time-resolved positioning accuracy, or star tracking. Under a contract with The University of Texas Center for Electromechanics (CEM), a prototype actuator has been designed, built and delivered by ADS International (Valmadrera, Italy). In addition to performance requirements, the hexapod operation has been scrutinized with regard to personnel and hardware safety and is equipped with limit switches and hard stops, that when engaged will not damage internal actuator components. Using modern modeling and computational techniques, the hexapod actuators were designed to provide the maximum hexapod operational envelope, while preventing the unintended impact to adjacent hardware. This iterative design/modeling process allowed the design team to include an adequate amount of excess travel for uncertainties in the existing telescope structure while meeting all of the science requirements. An overview of the HET layout is shown in Figure 2.

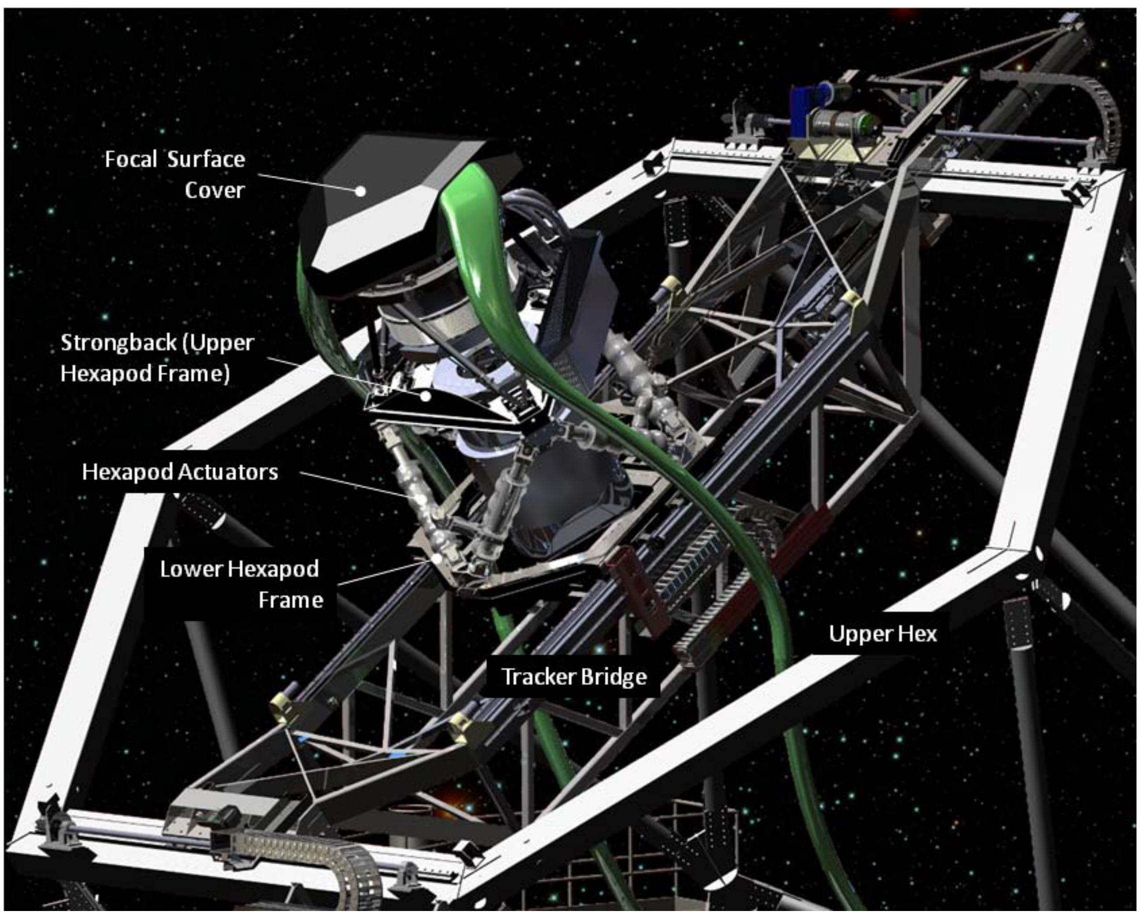

Figure 2. HET layout with major components

2. PERFORMANCE REQUIREMENTS

During the proposal and specification phase of the actuator design effort, a large number of detailed requirements were developed including everything from cabling to motor coolant specific heat. To keep within the scope of this paper, a list of top performance requirements are presented below. This paper will focus on the discussions and decisions that were made along the way in developing an actuator that meets or exceeds all of the requirements shown in Table 1.

Table 1. Hexapod actuator performance requirements

Parameter		Description	Value	Parameter		Description	Value
1	Actuator Operational Limits	Retraction	-45 mm	6	Actuator Position Accuracy	Pointing and Tracking	+/- 0.002 mm
	Out to +/- 8.5 deg tip/tilt	Extension	240 mm			Slewing	+/- 0.005 mm
2	Actuator Operational Limits	Retraction	-45 mm	7	Environmental Conditions	Normal Observing	-5 to 25^{o}C
	Pistoning out to 9 deg	Extension	260 mm			Marginal Observing	-10 to 30^{o}C
						Service	-10 to 35^{o}C
3	Actuator Travel Limits	Retraction Hard Stop	-75 mm			Survival	-25 to 45^{o}C
		Retraction Limit Switch	-72 mm			Shipping	-25 to 66^{o}C
		Retraction Software Limit	-60 mm				
		Home Position	0	8	Actuator Stiffness	End Mounts	250 N/micron
		Extension Software Limit	275 mm			Strut	400 N/micron
		Extension Limit Switch	287 mm				
		Extension Hard Stop	290 mm	9	Actuator Loads	Compression	30 kN
						Tensile	10 kN
4	Actuator Length	Pin to Pin Distance	1440.5				
	At Zero (home) Position	Between Wedges	1660.5	10	End Mount Rotation	In two axes	+/- 20 degrees
5	Actuator Speeds	Tracking	+/- 0-0.4 mm/s	11	Maximum Allowable External Temperature	Actuator exterior	0.5^{o}C
		Slewing	+/- 0-5 mm/s				

2.1 Actuator length and travel requirements

The actuator length and travel requirements were very carefully established using a commercially available, three dimensional modeling package which used a detailed and kinematically correct model configured by designers at CEM. Additionally, an Excel macro was written to control the CAD model, driving the telescope tracker to different regions of the operating space and then querying and recording the six actuator lengths[11]. This automated approach allowed the user to cover a very large portion of the operating space, record data, and increase confidence that maximum and minimum actuator lengths had been identified. This macro proved to be very useful throughout the design process and was later used as a tool to make sure that if any combination of actuators failed in extension or retraction, the actuator end mounts would not bind, and none of the optical hardware would impact adjacent hardware. In parallel to the CAD model based analysis, MATLAB and Simulink models were developed to dynamically evaluate actuator performance requirements necessary to meet HET tracking and slewing requirements. These models included system kinematics, sensors and control system simulations to ensure that adequate length and travel requirements were determined. Substantial effort was expended to correlate the CAD and MATLAB/Simulink results to improve design confidence.

2.2 Actuator speed and acceleration

Personnel from the McDonald Observatory developed a Tracker Movement Time (HX0050) document that served as the basis for the actuator speeds needed to achieve all the science requirements[12]. This document described many different travel scenarios required during observations (tracking the sky) and set limits for allowable ‘rewind’ times (slewing). Using an actuator acceleration of 2 mm/s^2 and the allowable times for science and rewind, we were able to calculate actuator tracking and slewing speeds, respectively, which are shown in Table 1. The current HET hexapod has the distinct reputation of frequently being the last piece of hardware in position before a new track can begin. Engineers working on the hexapod and actuator design were committed to helping shed this reputation and were able to configure the actuator drive train so that rewind requirements are achieved with about 10-15% margin.

2.3 Positioning accuracy

Perhaps the most important performance requirement is for the actuator to accurately achieve a specific time-resolved position and velocity (length and speed at the beginning of a tracking trajectory) over a wide variety of operational and loading conditions. Early hexapod and tracking control models were used to help establish the actuator positioning requirements for small movements (actuator travel less than 50 mm) and larger actuator movements (actuator travel up to 300 mm). Dynamic models showed that while tracking on the sky during closed loop operation (actuator speed of 0.4 mm/s and displacement of 50 mm or less) the hexapod actuators needed to be within +/-0.005 mm in order to meet the tip/tilt science requirement. Additionally, a similar analysis showed that following a rewind (or slewing) event (actuator speed of 5 mm/s and displacement of 300 mm or less), the actuators needed to be within +/-0.010 mm to meet the tip/tilt requirement of beginning a new track. Each of these accuracy results was reduced to one-half of their estimated amount and set as a performance goal in order to ensure an adequate margin of safety on the positioning accuracy. Additionally, MATLAB-Simulink models described in Section 2.1 were exercised to validate accuracy requirements for the hexapod and how hexapod errors impacted overall tracker errors.

2.4 Environmental conditions

As with most telescopes, the hardware must operate over a wide range of environmental conditions and the HET is no exception. One area that seemed to pose a challenge to the designers was the requirement to maintain flexible wiring/cabling insulation down to -10^{o}C. Many of the common (and less expensive) cable insulation materials provide adequate flexibility and operation down to -5^{o}C, which was deemed not adequate for marginal telescope operation. The final cabling solution for the actuator is a Lapp Olflex Classic CH which offers flexibility to -10^{o}C. Another strong consideration was the selection of lubricants and seals, which also had to operate down to these temperatures. Using an atmospheric chamber at their facility, ADS has verified the prototype actuator did not experience any noticeable changes in operation, due to changes in lubricant viscosity, seal friction, or dimensional changes during operation down to -10^{o}C.

2.5 Actuator and end joint stiffness

During the tracker design phase of this project, the hexapod actuators and end joints (one on each end of the actuator) were modeled as springs connecting the lower and upper hexapod frames and supporting the PFIP mass. A graphical representation of this model is shown in Figure 3.

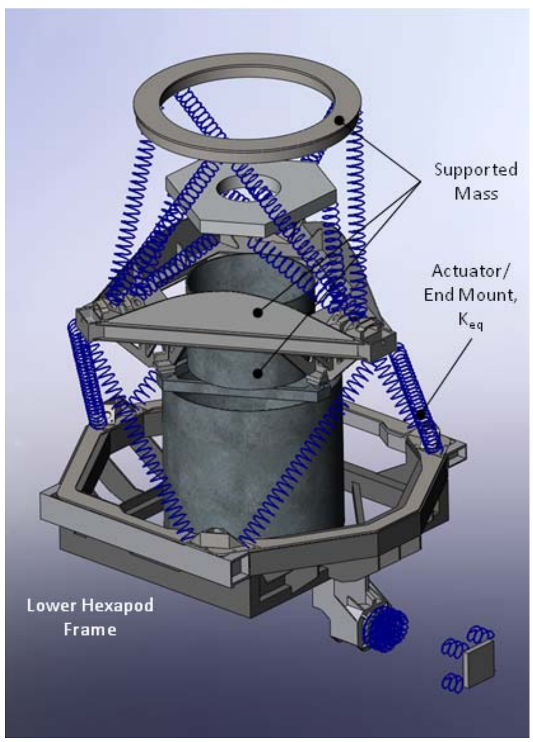

Figure 3. Spring-mass model for hexapod (lower set of 6 springs) and PFIP (upper set of 12springs) as well as springs in the lower right-hand corner representing a portion of the Y-axis drive

The purpose of this model was to determine the required actuator and end mount stiffness needed to achieve hexapod assembly stiffness greater than 10 Hz. The actuator assemblies (including end joints) are modeled as three springs in series. The first mode of vibration (with the PFIP rocking along the major bridge axis) is dominated by the lower hexapod frame stiffness in the region where the actuator bipod is located on an unsupported section of the lower hexapod frame. This first mode is mostly independent of the actuator assembly stiffness and the resulting fore-aft frequency is about 8.2 Hz. The second mode of vibration is orthogonal to the major bridge axis, is dependent on the actuator assembly stiffness, and has a side to side frequency of 13.4 Hz.

2.6 Actuator forces

Since the HET telescope sits at a fixed zenith angle of 35 degrees, the static forces in the six actuators are not equal, and have been estimated using typical modeling and analysis tools. The two actuators located on the front of the PFIP (downhill side) are the most heavily loaded at 25 kN in compression, however, this load varies between 22-28 kN during normal operation, depending on the tracker position. Moving uphill, the next set of symmetric actuators is loaded in tension over a range of 2-6 kN. Finally, the rearmost set of actuators is loaded in compression over a range of 1-7 kN. None of the actuators change between tension and compression during any telescope operation. It should be noted that due to the wide variation in loading between actuator pairs, the periodic maintenance schedule will include rotating the actuators from heavily to lightly loaded positions in order to extend actuator life. These force numbers were determined using both the CAD model software and the MATLAB-Simulink models described in Section 2.1.

2.7 End joint rotation

The end joints are traditional Universal joint (U-joint) type mounts and provide rotation in two axes orthogonal to one another. These joints offer a larger range of travel as compared to flexure joints, but usually come at the expense of lower stiffness and higher friction. The HET operating space requires the increased travel of these joints, and using the CAD model described above (Section 2.1), the joint travel is approximately +/- 6 degrees in each joint axis. Another follow up study that evaluated joint rotation during an actuator fault condition (extension or retraction), showed the joints could travel by as much as +/-20 degrees, presenting a more challenging joint design requirement than originally perceived.

2.8 Motor housing temperature

Measurements taken at the current HET facility indicated that temperature variations on hardware components of less than 1^{o}C reduced the likelihood of causing a thermal plume in the viewing space of the telescope. To provide a margin of safety, the external temperature requirement was to not exceed 0.5^{o}C above ambient air temperature.

3. COMPONENT DESIGN

The drive train components account for much of the actuator detailed design process which includes a servo motor, coupled to a worm shaft, driving a worm wheel mounted to a roller screw. An overview of the actuator layout is shown in Figure 4. The complete actuator assembly, including the motor and both end mounts is approximately 230 kg.

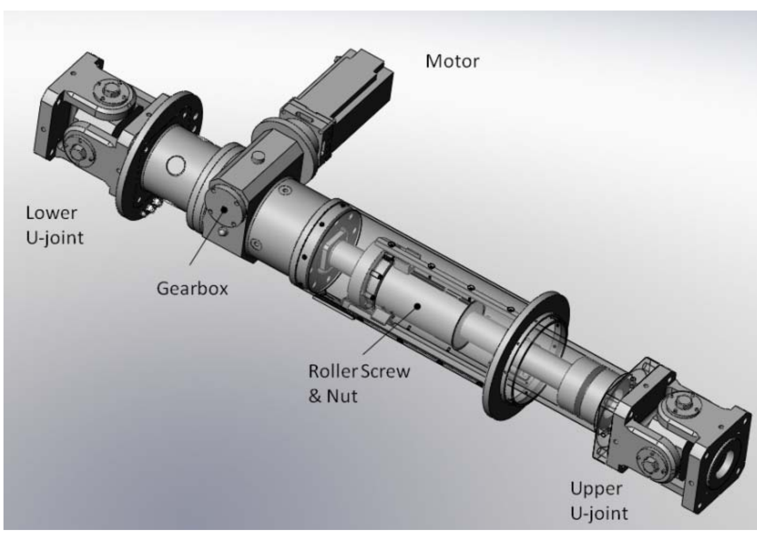

Figure 4. Actuator component layout

3.1 Drive motor and servo amplifier

Early in the actuator configuration process the design team seriously considered using a frameless servo motor, which would require a custom designed housing, allowing for a more compact design and integrated cooling passages. This approach has been used successfully on other projects by CEM, but the team decided to use a commercially available off the shelf (COTS) solution, primarily for long term availability of replacement (spares) and cost. A Danaher Motion AKM54G servo motor has been selected for this application. The selected configuration does not have a brake and uses a factory installed resolver for phase commutation. A summary of the motor performance specifications are shown in Table 2.

Table 2. AKM54G Motor Specifications

Parameter	Value
Rated Voltage	480 VAC
Rated Speed	2000 rpm
Rated Torque (at 2000 rpm)	12.3 N-m
Rated Power	2.57 kW
Peak Torque	37.8 N-m
Peak Current	14.9 A
Motor Constant, K_t	2.88 N-m/A_{rms}
Back EMF Constant, K_e	185 V/krpm
Resistance (line to line)	4.08 ohms
Inductance (line to line)	22.9 mH

Control of the ADS actuator requires a servo-amplifier capable of supplying the correct voltage and current to the AKM54G motors. A peak running current of 2.5 amps has been observed during prototype testing under peak load. The baseline control solution from ADS includes a GML152R5 Geo Macro Drive from Delta-Tau. While this system performed well during prototype testing at ADS, it does not lend itself to easily communicate with the final tracker controller, a dSPACE system. Therefore, a servo-amplifier from Danaher was chosen to replace the Geo Macro Drive. The S603-PB drive is capable of 3 amps of continuous current and 6 amps of peak current. It will communicate to the tracker controller, a dSPACE system, via PROFIBUS link.

3.2 Coupling

One of the safety features included in the actuator drive train is a backlash free torque limiting coupling. The coupling will completely disengage when subjected to a factory set predetermined torque level, but can be field adjusted within a certain range. The rational for this feature was to completely interrupt the drive train should the torque level be exceeded. The coupling must be reset in-situ by a person using a screwdriver through an access port in the side of the actuator, thus allowing for inspection of the surrounding area. A similar coupling has been used in other drives system as part of the HET Wide Field Upgrade[13].

3.3 Gear set

The actuator drive train includes a 60:1 zero backlash gear set manufactured by Cone Drive. ADS was responsible for designing and manufacturing the custom gear set housing and integrating it into the actuator. To manage the zero backlash condition, the gear set includes a split and preloaded worm shaft which must be set for the expected actuator load. Engineering support from Cone Drive played an important role in selecting the final gear set size, estimated life, efficiency, and helping reduce the likelihood of a stair-stepping condition that sometimes occurs in worm gear applications[14]. Laboratory tests with the actuator have confirmed the actuator is not back-drivable and does not exhibit any stair-stepping behavior. It should be noted that ADS has successfully used this gear arrangement in other actuator applications and always found the startup and running torques to be noticeably lower than the design values cited by Cone Drive.

3.4 Roller screw

The 60 mm outside diameter roller screw has a 12 mm/rev screw pitch which is used to convert the rotary motion of the gear train to linear motion of the actuator. The screw has a class G1 accuracy with an advertised screw error of less than 0.006 mm for every 300 mm of screw length. In fact, the screw that was delivered to ADS for the prototype actuator has an error of less than 0.004mm over the entire 400 mm length. The roller screw assembly includes a preloaded nut that is set according to the maximum expected actuator load. To help achieve the desired actuator stiffness, the roller screw shaft is supported by two sets of preloaded ball bearings.

3.5 Rotary sensor

Length measurement of the ADS actuator is performed using a rotary encoder mounted directly to the end of the screw. Given the known screw pitch and a well defined screw, very accurate length measurement is possible. The baseline rotary sensor was an EQN 425 from Heidenhain Corporation. This sensor has both incremental and absolute feedback. The relatively coarse, 13 bits per revolution, absolute information is used only to initially zero the controller. Then the higher resolution incremental feedback is used for control. It was decided to simplify the control and switch to an EQN 437 which has only absolute feedback. The EQN 437 outputs 25 bits per revolution and can distinguish 12 bits of revolutions. This sensor returns sufficient resolution for position control and does not require the control to perform any mode switching between feedback signals.

3.6 End joints

To achieve the desired stiffness, the U-joints on each end of the actuator are substantial and provide the necessary +/- 20 degrees of rotation in two axes. Each axis of the joint is supported by two adjustable tapered roller bearings. The ability to adjust the bearing preload, allows the user to find the correct balance between preload, stiffness, and smooth operation over the angular range of the bearing. A photo of the U-joint is shown in Figure 5.

3.7 Motor cooling jacket

ADS has designed a custom cooling jacket that surrounds the motor exterior and should provide the cooling needed to keep the motor external temperature within operational specification shown in Table 1. In this design, 'cold' coolant enters one end of the jacket, travels around the spiral coolant passages, and exits the other end of the jacket. Engineers at CEM have used this same cooling method for other servo motor applications and found it to be very effective. A photo of motor cooling jacket installed on the prototype actuator during some recent laboratory tests is shown in Figure 6.

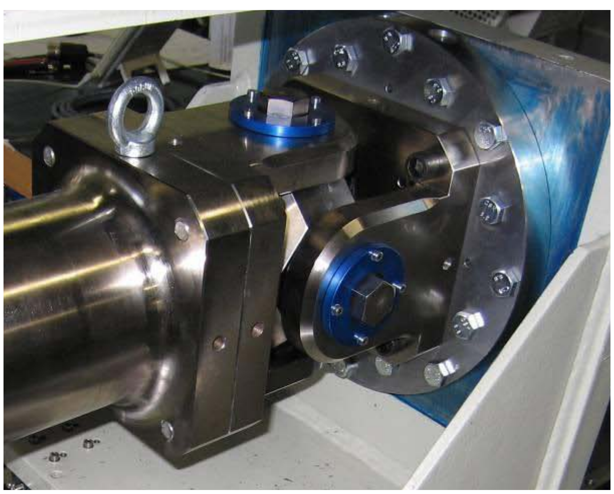

Figure 5. Actuator U-joint installed on test stand

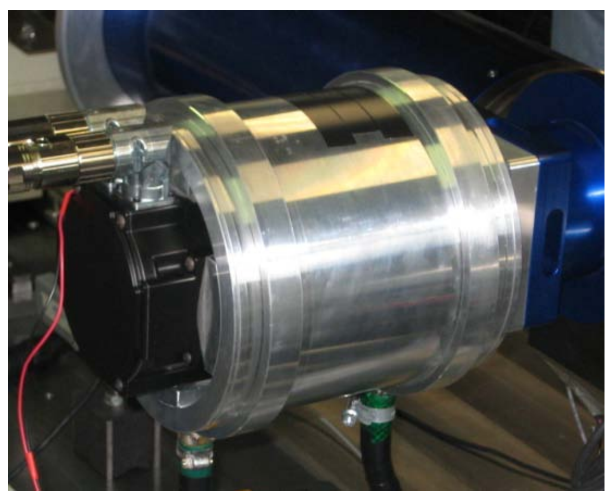

Figure 6. Motor cooling jacket installed on motor

laboratory testing

A complete set of laboratory tests were completed on the prototype actuator in May 2010 at ADS International facility in Valmadrera, Italy. A wide variety of tests were conducted on the prototype actuator including positioning accuracy at slewing and tracking speeds, stiffness measurements, speed and direction changes, smoothness of the U-joint travel, and operation down to -10^{o}C[15]. In the data figures that follow, following error is defined as the difference between the controller commanded position and the position measured on the internal rotary encoder; positioning error is defined as the difference between the controller commanded position and an external truth sensor (Heidenhain linear probe).

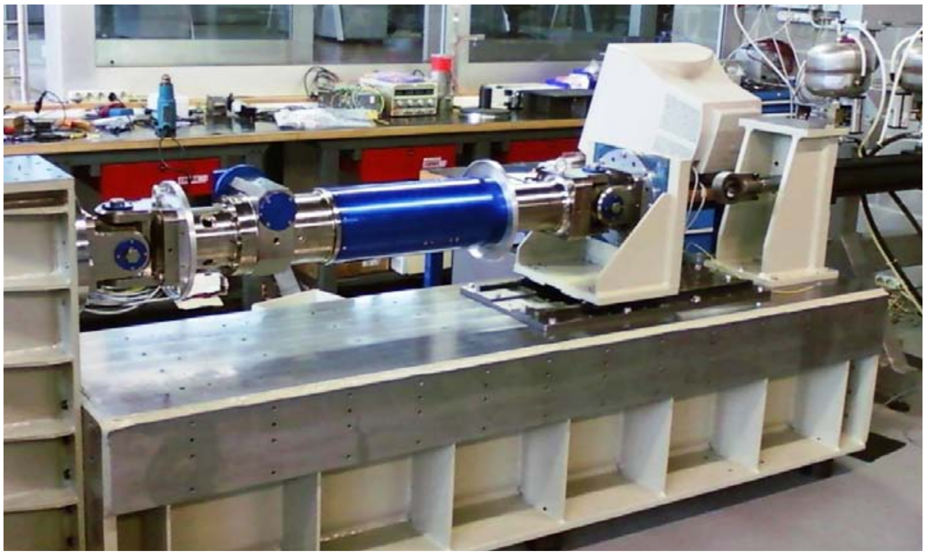

Figure 7. Prototype actuator installed in the partially assembled laboratory test stand

3.8 Position accuracy measurements

The data in Figure 8 were taken during a 50 mm tracking event at 0.4 mm/s with the prototype actuator loaded to 30 kN in compression. In this plot, the following error (red line) is less than +/-0.001 mm peak to valley; the positioning error (blue line) is less than +/-0.002 mm peak to valley.

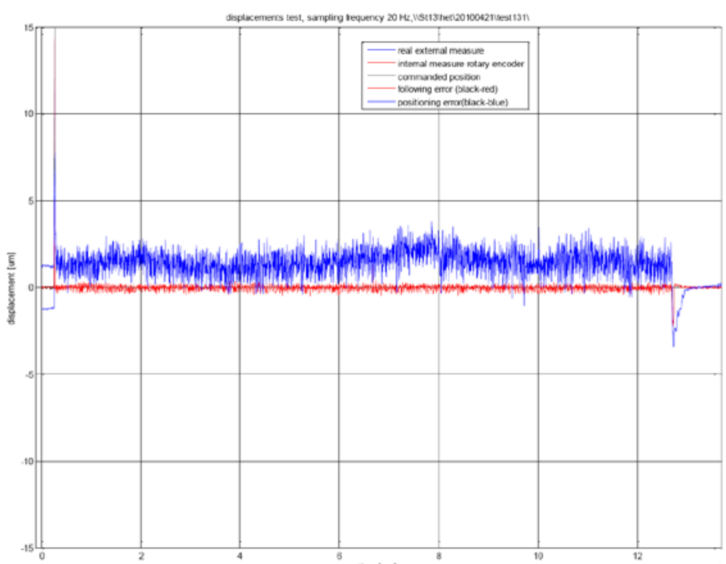

Figure 8. Actuator tracking measurement

3.9 Stiffness measurements

Figure 9 shows the measured results from the prototype actuator stiffness test with a compression load that varied between 22-28 kN, which is the expected load range on the front (downhill) actuators shown in Figure 2. In this test, the complete actuator assembly with end mounts installed (blue line) has a measured stiffness of 171 N/micron; a single end mount alone (green line) measured 571 N/micon.

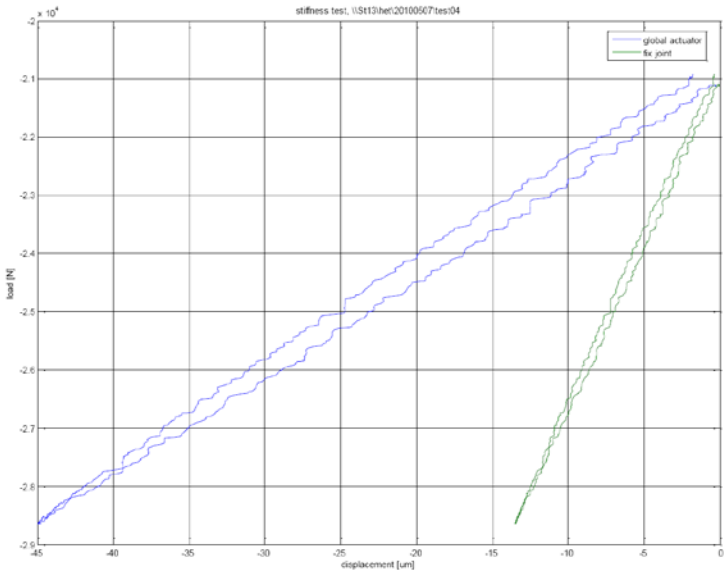

Figure 9. Actuator and end joint stiffness measurements

3.10Speed and direction changes

Figure 10 shows following error (red line) and positioning error (blue line) with the prototype actuator undergoing a sinusoidal motion of +/-10 mm with a frequency of 0.006 Hz and a 30kN compression load. This amplitude and frequency were chosen to represent an actuator changing direction and a speed range of 0-0.4 mm/s. In this test, the following error is less than +/-0.001 mm peak to valley; the positional error is less than +/-0.003 mm peak to valley. The peaks on the positional error plots are caused by uncontrollable load fluctuations in the test stand and directly proportional to the actuator stiffness.

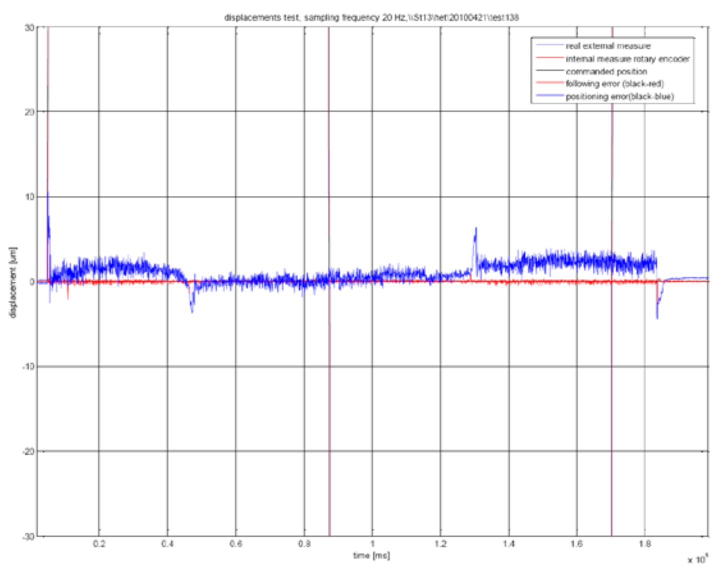

Figure 10. Actuator sinusoidal motion

3.11U-joint travel

Figure 11 shows the actuator mounted in the test stand at an angle of about 18 degrees. As the sliding end of the actuator (shown on the left) traverses back and forth, the U-joints travel through about 4 degrees of angular rotation. The purpose of this test is to determine the effect on the actuator tracking performance due to the rotation of the end joints.

Figure 11. Test stand setup for evaluating U-joint motion

The results from the U-joint test are shown in Figure 12. The following error (red line) does not indicate any effect due to the rotation of the end joints. The positioning error (blue dashed) of the actuator is still within +/-0.002 mm peak to valley.

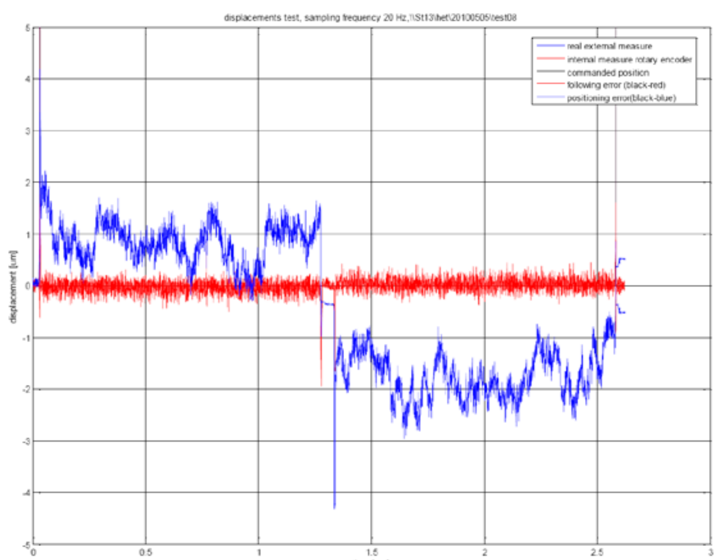

Figure 12. Evaluation of U-joint travel

3.12Operation at -10°C

The purpose of this test was to determine if there were any adverse effects on actuator functionality at low temperatures. To conduct the test, the actuator was placed in a vacuum bag and then the climatic chamber at -10°C for more than 12 hours. The results of the test demonstrate the electronics on board of the actuator are functional and the actuator is controllable at temperature below -10^{o}C. Additionally, the motor current measurements indicted no increase in current (due to binding) at these temperatures.

4. CONCLUSIONS

Engineers from UT Austin (McDonald Observatory and Center for Electromechanics) and ADS International (Valmadrera, Italy) worked together to develop a set of robust, high precision, hexapod actuators that meet all of the performance and safety requirements needed to help insure a successful HETDEX program. Specifically, engineers from the UT McDonald Observatory have extensive knowledge of the current system, many of which were involved during the design and construction of the original HET system. CEM has years of experience in developing robust electro-mechanical systems for use in many demanding military applications. ADS International personnel have been able to leverage years of engineering design experience in support of other telescopes, including the Large Binocular Telescope and the Dark Energy Camera for the Fermi Lab Blanco Telescope. Following the successful completion of the prototype actuator design, build and test, ADS International was given the go-ahead to begin fabrication and assembly of the full set of actuators for use on the Hobby Eberly Telescope with an expected delivery of August 2010.

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