Cobra – a Two-Degree of Freedom Fiber Optic Positioning Mechanism

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Abstract—The Wide-Field Multi Object Spectrometer (WFMOS) along with corrective optics will mount in place of the Secondary Mirror of the Subaru telescope on Mauna Kea, Hawaii to allow simultaneous observations of cosmologic targets. It will conduct large scale Galactic Archeology and Dark Energy surveys to help unlock the secrets of the universe. The key enabler of the observations is an array of 2400 Cobra optic fiber positioners made from very small rotary motors which were developed for this purpose. Cobra is a two degree of freedom mechanism that can position an optical fiber in the prime focus of the telescope to a precision of 5 µm. It is a theta-phi style positioner containing two rotary piezo tube motors with one offset from the other, which enables the optic fiber to be placed anywhere in a small circular patrol region. The patrol diameter of the actuator is large enough to obtain 100% sky coverage of the close packed hex array pattern of positioners. The name Cobra was chosen because the positioner resembles a snake ready to strike.[1][2]

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1. INTRODUCTION

WFMOS is a ground based astronomical instrument that is scheduled to be commissioned on the Subaru Telescope on Mauna Kea, Hawaii in 2013 (Figure 1). It has an array of fiber positioners that feed light from a 1.5 degree field of the sky to a visible spectrometer for red shift observations of 2400 cosmological targets simultaneously. The light is transferred to the spectrograph using 2400 f/2.4 fibers with 107µm cores. This enables for the first time, large scale Galactic Archeology and Dark Energy surveys to help unlock the secrets of the universe. The key enabler of this new capability is the Cobra fiber positioner, which is composed of the world's smallest rotary motors which were developed specifically for this purpose.

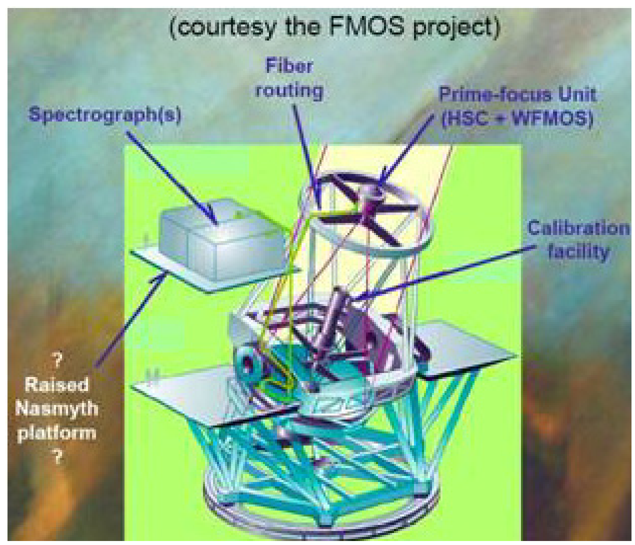

Figure 1 – WFMOS on the Subaru telescope

2. COBRA DESIGN OVERVIEW

Each Cobra is a two degree of freedom theta-phi style mechanism containing two rotary piezo tube motors with one offset from the other, which enables the optical fiber to be placed anywhere in a 9.5mm diameter patrol region. The patrol region of the positioner is such that there are no gaps in sky coverage between the Cobra positioners.

For cost savings the Cobra actuator does not incorporate encoders on the 4800 degrees of freedom. Instead they are controlled in an open loop mode with position information obtained after the positioner field is stopped and imaged. Their positions are verified by back illuminating the optical fibers and measuring their locations using a Charge-Coupled Device (CCD) metrology camera. Multiple

[1] 978-1-4244-2622-5/09/$25.00 ©2009 IEEE
[2] IEEEAC paper #1185, Version 5, Updated January 5, 2009

iterations are required for the Cobra positioner to converge on its cosmologic target.

The first stage of the Cobra positioner incorporates an ultrasonic tube motor, with a hollow shaft to allow the optical fiber to be routed through the center of the mechanism. The second stage also utilizes an ultrasonic tube motor and its rotation axis is offset from the first stage axis by half of the patrol area radius. The fiber is mounted on an arm that is attached to the output shaft of the second stage motor that also is half of the patrol area radius, which is shown in Figure 2. The Cobra positioner also needs to incorporate hard-stops so that it can be driven to its "home" position in the event that the metrology loop is broken and its current position is lost (possibilities would include power failure, metrology camera malfunction, etc). Cobra also needs to be able to rotate 0°-360° so a floating hard stop concept was implemented.

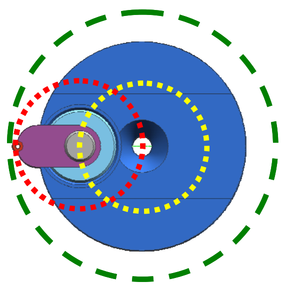

Figure 2 – Theta-Phi Patrol Area

Geometric Constraints

In the WFMOS instrument each of the 2400 Cobra positioners are integrated onto a common optical bench in a hexagonal close-packed array mounted on 8mm centers. To allow for machining tolerances and true position errors on the optical bench the outer diameter of the Cobra was constrained to be no more than 7.7mm in diameter. To allow for 100% coverage of the focal plane a patrol diameter of 9.5mm was chosen. To avoid interferences with neighboring positioners no part of the mechanism, other than the fiber arm, is allowed to exceed the 7.7mm diameter. The overall height of the Cobra positioner is not constrained, but efforts were made to keep Cobra as short as possible to reduce the effects of gravity sag.

Table 1 – Geometric Constraints

Requirement	Value	Units
Positioner External Dia.	≤ 7.7	mm
1st Stage Internal Dia.	≥ 1.2	mm
2nd Stage Offset	2.375	mm
Overall Length	n/a	mm
Hard Stop Rotation	≥ 360°	deg

Performance Constraints

The performance goal of the Cobra positioner is to place the fiber tip within 5µm of its cosmological target in the focal plane. To achieve the positioning goal the motors must be able to make very small steps. The motors must also provide adequate torque to overcome the twisting of the optical fiber and friction within the positioner.

Table 2 – Performance Constraints

Requirement	1st Stage	2nd Stage	Units
Min. Step Size	≤ 0.084	≤ 0.167	Deg
Stall Torque	≥ 0.346	≥ 0.337	mN-m
Speed	≥ 1.0	≥ 1.0	Rev/sec

3. TRADE STUDY

The Cobra Positioner with two piezo tube motors in the Theta-Phi configuration was chosen for WFMOS because it was determined the tube motors were most likely to meet the requirements of size, torque, resolution, and cost. At the time of the WFMOS design study, piezo tube motors had only been demonstrated as breadboards at larger sizes than required for the WFMOS Cobra Positioner [1]. The piezo tube motors had not been evaluated for angular resolution and torque output, which are the most important requirements for the WFMOS instrument. While the piezo tube motor development was underway, a variety of other positioner concepts were explored in the event that the tube motors would not meet performance requirements. Luckily, the tube motors performed exceptionally well and as a result these alternate configurations were not prototyped.

Theta-Phi Configuration

The key to making the Theta-Phi configuration work is having a second stage tube motor that can provide the required torque and step sizes. As a general rule, as the piezo tube motor diameter decreases, the angular resolution increases and the torque output decreases. With that in mind, it is preferable to maximize the motor sizes as much as possible. However, to achieve the packing density required with 100% sky coverage and minimize collision issues with neighboring positioners, it is important to design the second stage housing such that it does not overhang the first stage housing.

The first stage envelope is large enough that an ultrasonic ring motor [1] or a commercially available DC brushless motor with a planetary gear-head could be used in place of the piezo tube motor. The downside of using a DC brushless motor is that two different types of electronics are needed (one for the DC and one for the piezo tube), which adds cost and complexity to the system. The planetary gear-head needed with a DC brushless motor also creates wind-up and backlash issues. The ultrasonic ring motor is actually preferable to a piezo tube motor for the first stage because it is much shorter and would make a stiffer mechanism. Unfortunately the design of the ring motor does not lend itself to miniaturization without considerably affecting its ability to make small rotational steps.

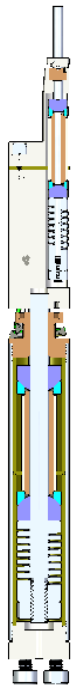

Figure 3 – Theta-Phi Configuation

Theta-Phi – In-line Concept

If the smaller piezo tube motor needed for the 2nd stage offset configuration failed to meet its performance specifications, then the fallback configuration would utilize two larger motors (tube or DC brushless motors). An offset of the 2nd stage shaft is still required so the output shaft of the 2nd stage motor is tied to the offset shaft using a pair of gears. For the same reasons mentioned earlier, utilizing gears creates problems with wind-up and backlash. Utilizing a torsional spring can eliminate both wind-up and backlash. This was the primary fall back design if the tube motors didn't meet performance specifications.

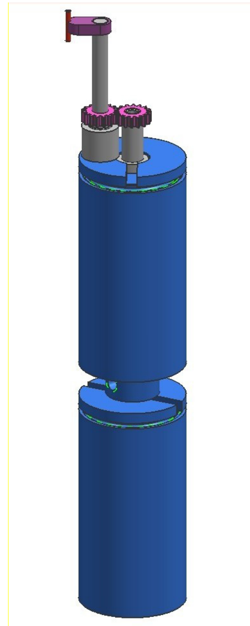

Figure 4 – Theta-Phi – In-line

Theta-R Concept

An intuitive concept for patrolling a circular region is the theta-R concept where the first stage provides 0°-360° motion, and the second stage moves radially from the center of the patrol region to its edge. The motor needed for the first stage of this concept could be any of the first stage motors discussed with the Theta-Phi concepts. The critical dimension for the second stage linear motor is its length. The length of the motor would have to be no larger than one half of the diameter of the first stage. New Scale Technologies offers a piezo driven motor called a "Squiggle" motor. The smallest Squiggle motor is 6mm long, which is greater than half the diameter of the first stage needed. Another method of mounting the Squiggle motor that would allow a 6mm long motor is if the output shaft of the motor is held at the edge of the patrol region. The fiber would then be mounted to the motor stator. Disadvantages of this layout are that the structure required to support the output shaft would extend beyond the patrol region and create a collision hazard for neighboring positioners. A method of maintaining the fiber in a vertical orientation would also be required, which at first glance appeared to be complicated.

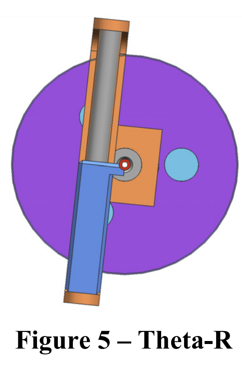

Figure 5 – Theta-R

Theta-R – Flexure Concept

The last concept that was explored was a variation on the above mentioned Theta-R concept. Instead of using a horizontally mounted linear motor, the linear motor is rotated vertically. To achieve radial motion, a flexure could be utilized such that one end of the flexure is fixed, the linear motor is mounted in the middle of the flexure, and the fiber is mounted on the free end. From a maneuvering stand point this concept is just as elegant as the 2nd stage off-set Theta-Phi positioner because the fiber can be retracted to within the first stage housing diameter to avoid collisions with neighboring positioners. One of the drawbacks to this design is the precision machined flexures that would be required. Also, slight variations in thicknesses at each of the four flexure points due to machining tolerances can cause the fiber to tilt. A guide feature could be added to maintain the fiber in a vertical orientation, but just like with the other Theta-R concepts this feature would be complicated.

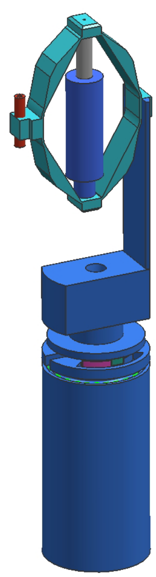

Figure 6 – Theta-R with Flexure

Other Concepts

One other concept that has actually been built and tested is the Echidna fiber positioner [2]. It operates using a long spine attached to a sphere that is rotated by a piezo actuated tube. The Echidna positioner allows two neighboring fibers to get very close to each other (less than 1mm), which is much better than the Cobra positioner, which can only place neighboring fibers 2mm apart. The downside of the Echidna positioner is its long spine geometry which tilts off axis and out of the focal plane to find targets which reduces the optical throughput of the fiber system requiring longer observations for the same amount of photons on the detectors of the spectrometer. This of course increases survey time.

4. Piezo Tube Motor Development

Introduction to Piezo Tube Motors

The first piezo electric tube motor was a rotary style motor conceived more than 60 years ago by Williams and Brown (1948) [3]. This motor uses an orbiting stator to engage a round shaft or gear where tangential contact produces rotation. In 1995, a tube style rotary motor was demonstrated by Morita [4], which uses a thin walled piezo electric cylinder. A miniaturized rotary motor, using two piezo plates and a hollow metal tube, was demonstrated by Koc, Cagatay and Uchino [5] in 2002.

Benefits of piezoelectric actuators include excellent responsiveness and conversion efficiency from electrical energy to mechanical energy. Piezoelectric based actuation has three broad categories: stacks, benders, and motors. Since the strain of the piezoelectric material is relatively small multi-component structures are needed to produce longer travel motion. Piezoelectric motors increase the displacement by providing many small steps to a moving element. There are many different types of piezoelectric motors and the main categories are linear stepper motors, linear tube motors, rotary tube motors, and ultrasonic motors (ultrasonic motors can be divided into standing wave and traveling wave). Linear stepper motors include inchworm motor style, a stick and slip actuator, and an impact drive motor.

For the Cobra positioner, a tube style rotary motor was chosen. Tube style motors consist of two general subassemblies, a stator and a rotor. In this configuration the piezoelectric plates are used to mechanically excite the first resonant bending mode of the stator assembly, providing mechanical energy. Tube style motors rely on mechanical excitation of the first bending mode of the stator assembly. Mechanical response is greatest at resonance. Tube style motors also rely on excitation of the orthogonal bending mode, or simply stated, bending on the Y-Z plane (motor phase 1) and on the X-Z plane (motor phase 2). It is important that the natural frequency and mechanical loss factor (Q) of the two orthogonal modes be matched and that the deviation from pure orthogonal bending between the modes be minimized. With a stator assembly optimized for a piezo tube motor application the electrical drive system completes the system.

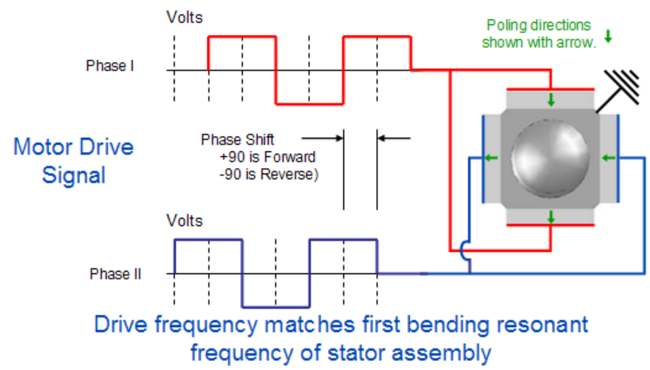

Figure 7 – Motor Drive Signal

A two phase drive system is illustrated in Figure 7. Each phase operates a mechanical phase of the stator assembly as indicated by the red and blue traces. Each driver phase actuates the piezoelectric material at the first mechanical resonant frequency of the stator assembly to excite its orthogonal bending modes. A close look at the driving waveforms of the two phases reveals a time based 90° phase shift between them. The mechanical response of the stator assembly, therefore exhibits a 90° phase shift between the first bending orthogonal modes. The phenomenon is illustrated in Figure 8.

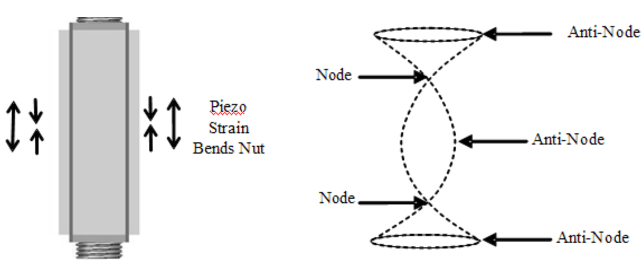

Figure 8 – Stator Mechanical Response

Notice the circular lisajou shape on the XY plane at each of the anti node points. The transfer of mechanical energy from the stator to the rotor takes place at the anti node points. When exciting the first bending mode in this fashion the radial displacement is largest at the anti-node points causing the stator to contact the rotor. The circular lisajous always moves tangential to the surface of the stator and when it makes contact it imparts a torque causing the rotor to turn. This is analogous to an inverted hula-hoop.

Cobra Motors – Version 1

Early motor research was focused on empirically studying variations in motor design parameters and their impact on motor performance. To do this, prototype motors were developed with the flexibility to adjust key parameters and allow researchers to explore the design space they share. This study was directed at determining optimal preload, contact angle and contact radius between the two elements. The results were then applied to the design and development of five prototype models for each of the two stages (vendor part numbers SQR-6.2 and SQR-3.4) of the Cobra positioner, which are 6.2mm and 3.4mm across respectively. Average motor performance results are shown in Table 3 compared to motor specifications based on preliminary Cobra system design. The Version 1 motor testing allowed an analytical model to be created to predict motor behavior under various operating conditions and to estimate performance of other sized motors.

Table 3 – Version 1 Motor Performance Results

Parameter	SQR-6.2		SQR-3.4	
	Spec	Actual	Spec	Actual
Min. Step Size	≤ 0.06°	0.04°	≤ 0.13°	0.07°
Stall Torque (mN-m)	≥ 0.70	2.9	≥ 0.69	1.6
Speed (rev/s)	≥ 1.0	≥ 5.0	≥ 1.0	≥ 5.0

Cobra Motors – Version 2

Changes in WFMOS design parameters required a motor size reduction from the Version 1 motors. The Version 2 motors were required to be 30% smaller to fit the 7.7mm diameter Cobra positioner, which resulted in motors measuring 4.4mm and 2.4mm across (compared to 6.2mm and 3.4mm). Other design changes that were made to the Version 2 motors were focused on improving lifetime performance, and optimizing resolution and torque capabilities. A detailed image of the motor is shown in Figure 9.

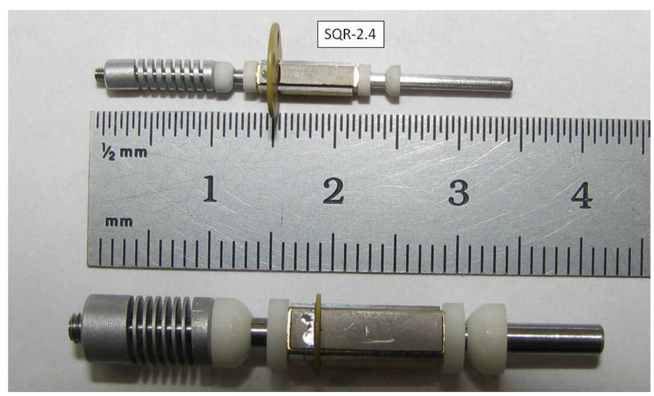

Figure 9 – Version 2 Motor Design

Compared to the Version 1 motors, the major difference with the Version 2 motors is a stator end cap that is bonded to each end of the motor body tube. Both the stator end caps and the rotor end caps are made of alumina ceramic. This design provides harder contact materials and an enlarged contact radius that allows for a softer tube material (brass 360 for example). The softer tube material increases the frequency of the first bending mode, which provides better torque and step size performance and less input energy.

The stator length was tailored to have higher motor frequencies for easier drive, but not too high to affect torque output. For the SQR-2.4, the piezo thickness was increased from a nominal 0.22mm (a value that is proportional to 3.4 and 6.2 motor sizes) to 0.3mm by reducing the thickness of the tube. The increase in piezo volume will increase the torque output with the same applied field strength. For the SQR-4.4, as the predicted torque output was sufficient, the piezo thickness was reduced from 0.45mm to 0.3mm to allow a lower drive voltage. The resulting piezo volume changes are 36% increase for SQR-2.4 and 45% less for SQR4.4. The contact radius for SQR-2.4 is 1.33 times the nominal and for SQR4.4 it is 1.53 times the nominal. These changes resulted in better torque and step size performance compared to the Version 1 design.

Table 4 – Version 2 Motor Performance Results

Parameter	SQR-4.4		SQR-2.4	
	Spec	Actual	Spec	Actual
Min. Step Size	≤ 0.084°	0.06°	≤ 0.167°	0.1°
Stall Torque (mN-m)	≥ 0.346	3.0	≥ 0.337	0.6
Speed (rev/s)	≥ 1	≥ 2	≥ 1	≥ 2

5. COBRA POSITIONER DESIGN

In piezo tube motors the stator assembly requires very particular dynamics to operate properly. Any influence on its mass stiffness balance can have a negative effect on motor performance. Shaft preload is also very important and affects the transfer of mechanical power from the stator to the rotor. Tube dynamics and preload where given particular consideration in the motor integration design.

To obtain high radial stiffness and durability, bushings were used to stabilize the rotor shaft of each stage. The stator mount ring also constrains the stator in position inside the housing. In this configuration it is a challenge to avoid over constraining the motor. If not done properly, undesired loading on the mount ring, which affects the stator assembly dynamics, and excessive radial loading between the rotor shaft and bushings, could occur. This effect could be induced by an error in the linearity and coaxial position between the rotor shaft and bearing axis. These problems were avoided using proper system design and assembly techniques.

Using the shaft to position the motor at the bearing axis first, the stator assembly mount ring is allowed to float radially allowing the freedom to be located collinear and concentric to the bushing axis. The rotor shaft is allowed to float axially in the bushing. This allows the motor to float on axis, relative to the bushings, when the mount ring is locked into place. The result is a well constrained system prepared to meet system performance requirements in a repeatable fashion (Figure 10).

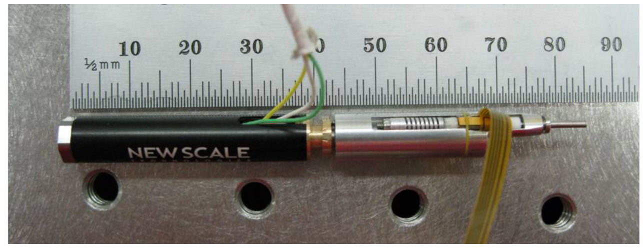

Figure 10 – Cobra Positioner

6. COBRA PERFORMANCE TESTING

After the prototype Cobra positioners were assembled and tested by New Scale Technologies they were delivered to JPL for further performance testing. The goal of the testing performed at JPL was to determine whether the positioner could achieve a final positioning error of less than 5µm and to evaluate how many open loop iterations would be needed to achieve that error.

Test Setup

The test was setup to be a good analogy of the system that WFMOS will use to “close the loop”. The fiber that is mounted to the positioner is back-lit using a Light Emitting Diode (LED), the fiber is imaged onto a CCD and centroided to determine the (x, y) position of the fiber, and then that (x, y) position is relayed back to the positioner software to determine what the next move should be. A translation stage is utilized to provide image scale so that the positions provided by the CCD are computed properly. This was done by applying a known translation and seeing how many pixels the image moved on the CCD. The resulting image scale was 6.825µm/pixel (actual pixel size is 7.4µm). Figure 11 shows the test set up used. The CCD that was used was a QSI 540i camera with a Kodak KAI-04022 CCD chip that measures 2048 pixels x 2048 pixels (15.15mm x 15.15mm). The Cobra positioner was driven using New Scale Technologies MC-1000 electronics that were customized with an inductor that matches the motor capacitance.

Software

MATLAB was used to determine the centroids of the fibers using a .tiff image file from the CCD camera. The fiber image was approximately 16 pixels across, which provides sub-micron centroiding accuracy. MATLAB was also used to take the measured position of the fiber and compute the required motor angles and steps needed to reach the target. Custom software provided by New Scale Technologies was used to command the two motors. Input parameters for the motors are: forward/reverse, motor steps, pulse length, and time between steps.

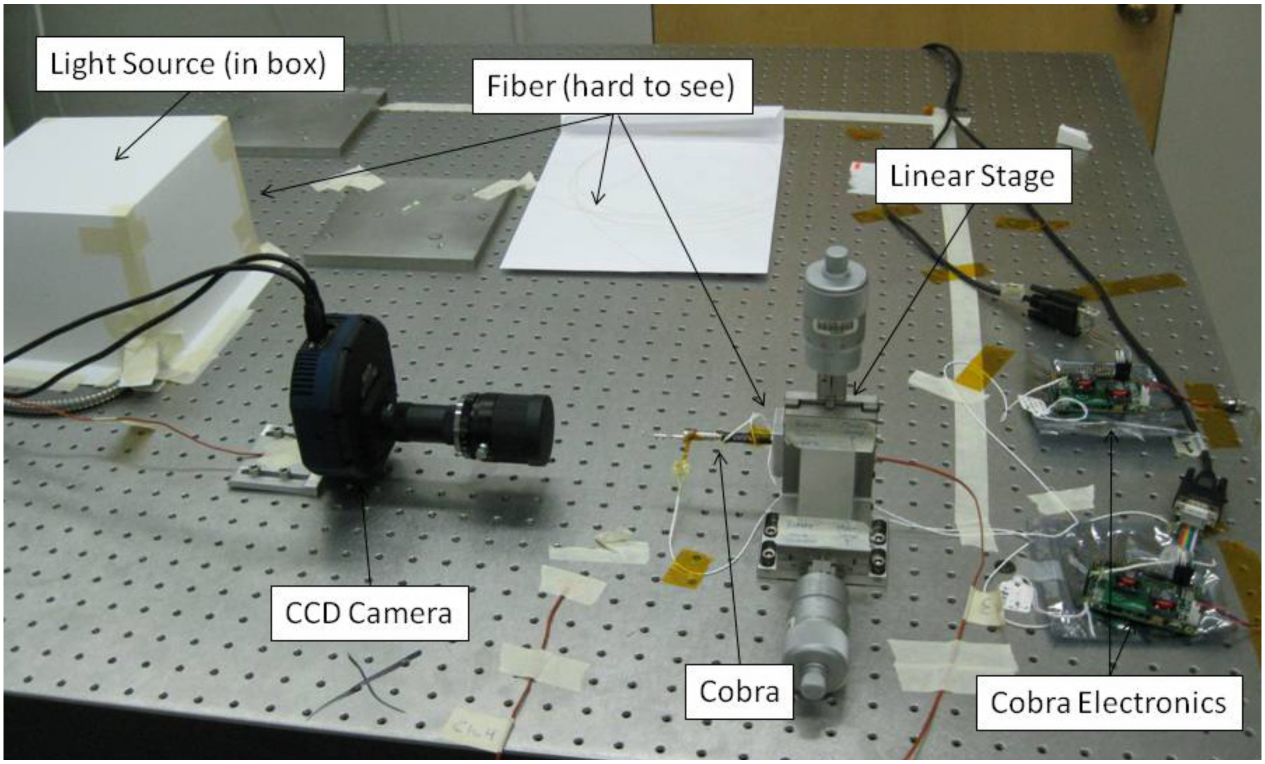

Figure 11 – Test Set Up

Metrology

There are three key dimensions of the Cobra positioner that needed to be determined: location of the first stage axis, the offset of the second stage axis, and the distance from the optical fiber to the second stage axis. The location of the first stage axis was determined by rotating the second stage motor while taking a series of images. A circle was best-fit to those points, where the first stage axis is at the center of the circle. The second stage offset (R1) and optical fiber arm distance (R2) were determined with the same method. The radius of the best-fit circle is R2, and the distance from the center of the second stage circle to the first stage circle is R1. The as measured values are shown in Table 5.

Table 5 – Key Measured Dimensions

Dimension	Value	Units
2nd Stage Offset (R1)	1.735	mm
Fiber Arm Distance (R2)	2.341	mm
Patrol Area Diameter (2[R1+R2])	8.152	mm
"Dead Area" Diameter (2[R2-R1])	1.212	mm

It should be noted that because the distance from the fiber to the second stage axis and the second stage offset distance are not the same then there is a small region at the center of the positioner that cannot be reached. The "dead area" measured on the prototype only reduces the patrol area by 2.2%. Better machining tolerances and assembly jigs are hoped to reduce this effect in the future.

Calibration

Before testing began, each motor was characterized in the forward and reverse directions by applying a set number of steps or pulses and measuring the angular distance travelled. The angle moved was then divided by the number of motor steps and the average step size was assigned to that region of motor motion. Figure 12 shows the results of the 1st stage motor calibration in the forward direction. Comparing the relative distance between lines it can be seen that there is a fair amount of step size variance in the motor. Each motor demonstrated similar behavior in both directions.

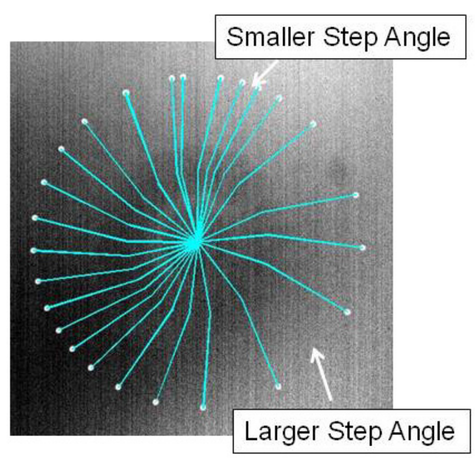

Figure 12 – 1st Stage Motor Calibration – Forward

A method of "continuous calibration" was also implemented to help reduce the number of move iterations needed once the fiber is close (~5°-10°) to the target. Continuous calibration was achieved by taking the average step size from the previous move and averaging that with the previous predicted step size. A key aspect to this method is that it was only implemented if the previous move stayed within the same motor region. Although the effect of this method wasn't studied extensively, it was observed to cut down on the number of move iterations between 30-70%. To take advantage of the continuous calibration method, 118 targets were tested in a sequence that progressively moved around the patrol region such that the knowledge gained from previous targets would help improve performance for future targets.

Test Results

After the initial 118 targets were tested, another 29 targets were chosen at random to evaluate the performance of the Cobra positioner. The test sequence for a target was to move the motors from their hard stop locations to the targets by commanding the motors by a predicted number of steps. After the move, an image was taken of the optical fiber. The actual position of the optical fiber was then determined, and another iteration of moving and imaging was performed until the fiber was within 5µm of its target. Figure 14 is an example plot of the distance to the target after each move iteration. The same target was used during the initial calibration effort and three subsequent attempts after the calibration was completed. The effect of the continuous calibration method is the reduction of move iterations by half.

Figure 15 shows the percentage of the targets that were positioned within the target range after each move iteration. At the beginning of testing, the goal was to demonstrate that the Cobra Positioner would converge to at least 90% of the targets to within 5µm after five move iterations. It was actually demonstrated that six iterations were needed to converge on more than 90% of the targets. If the target range is opened up to 10µm then 90% of the targets were converged upon. If the target range is opened up from 5µm to 10µm, the impact on the WFMOS instrument is less optical throughput, which leads to longer exposures and less science data collected. Adding the additional move iteration is a more efficient method of getting more science targets with less time.

Based upon this testing the Cobra positioner has similar positioning performance as the Echidna positioner [2] with the noted difference being that the Cobra positioner can reconfigure in less than one second compared to the 3 plus seconds needed to reconfigure Echidna.

7. CONCLUSION

The Cobra fiber positioner was developed for the WFMOS instrument to enable 2400 cosmological objects to be analyzed simultaneously with a spectrograph. The Cobra positioner required newly developed piezo tube motors in order to position an optical fiber within 5µm of a cosmological target. Through a series of design iterations, the piezo tube motors were optimized such that they could make step sizes smaller than 0.065° and provide more than 3.0 mN-m of torque.

The Cobra positioner was tested in a lab environment in a manner that simulates its use on the Subaru telescope. The positioner was controlled in open loop and used a CCD camera to image its optical fiber to determine its location. Over 100 simulated cosmological targets were tested using the Cobra positioner and showed that the Cobra Positioner can converge on over 90% of its targets within 5µm in six open loop move iterations.

Lessons Learned

The majority of the problems that arose during the Cobra prototype testing were related to the floating hard stops (Figure 13). Not enough time was spent designing the hard stops and as a result it played a noticeable role in testing. The 2nd Stage hard stop had a propensity to fall out during installation of the fiber arm. This was due to the preload spring for the SQR-2.4 motor being able to compress, which allows the output shaft to rise up enough that the hard stop could come out of its groove. In future builds the hard stop needs to be taller and the groove needs to be deeper. The hard stop also tended to get cocked, which caused increase friction within the 2nd Stage that required a few additional move iterations to overcome. A hard stop that has a longer arc length and a reduction of fillet radii in the hard stop groove should mitigate these problems.

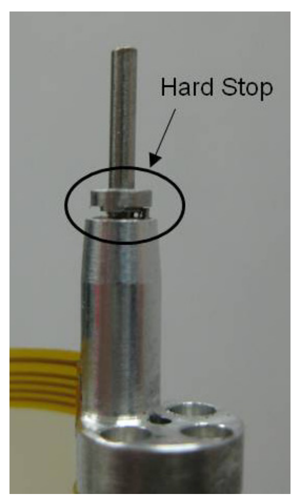

Figure 13 – 2nd Stage Hard Stop

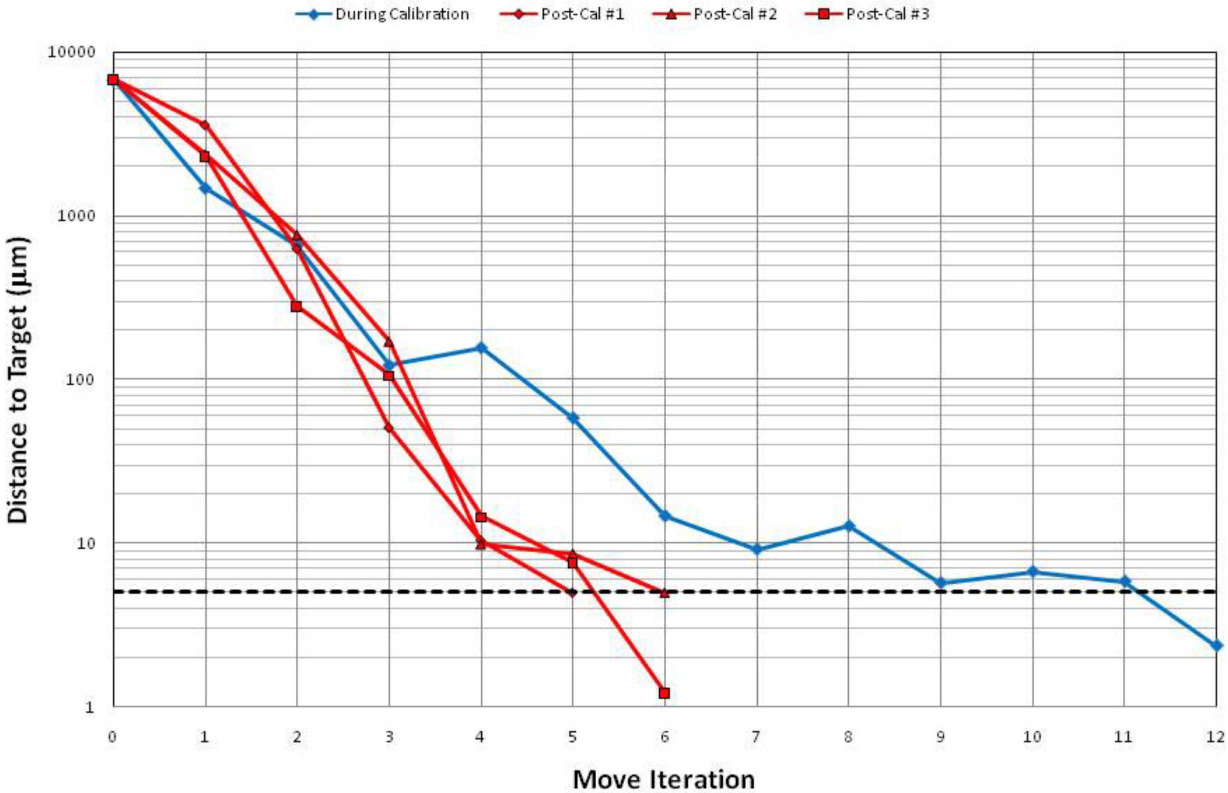

Figure 14 – Move History Example for a Target During and After Calibration Runs

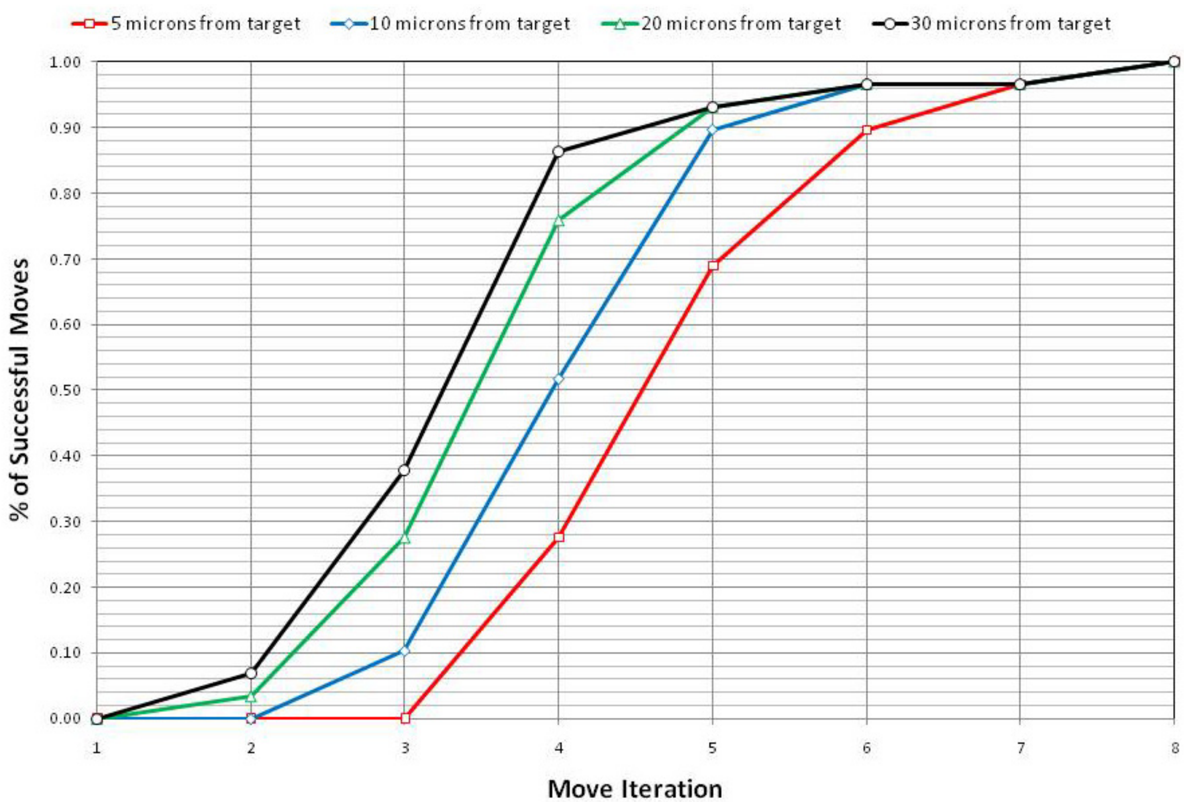

Figure 15 – Percentage of Positioners within Target Range After Each Move Iteration

For the majority of the targets tested there was a considerable amount of overshoot and undershoot on the first few move iterations. Encoders were not originally included in the design of the Cobra positioner due to a lack of cost effective commercially available encoders at the very small sizes needed. If a viable (small and cheap) encoder can be found it would likely reduce the number of move iterations needed from seven down to three or four. An 8-bit encoder would have more than enough resolution to take care of the larger moves then open loop fiber imaging can make the fine tune adjustments.

Future Work

The next phase of the project will include a high fidelity design and test cycle. Design modifications will be incorporated to address issues discovered in the prototype testing and incorporate features to reduce high volume manufacturing costs. A test bed will be built that contains 10-30 Cobra positioners working simultaneously with the customized WFMOS motor drivers. This test bed would allow for the development and testing of control and collision avoidance software and would give a much better projection of the performance of 2400 positioners.

Although the Cobra design is made up of low wear components and only has a 22 hour continuous operation life requirement (which has 10% duty cycle start/stops imbedded), characterization of performance versus lifetime at an environment that represents Mauna Kea will be conducted. Throughout the prototype testing discussed in this paper there were no apparent effects of performance degradation, but temperature and humidity were at ambient conditions.

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REFERENCES

[1] Micromechatronics, Inc. website http://www.mmech.com/

[2] Masayuki Akiyama, et al., "Performance of Echidna fiber positioner for FMOS on Subaru," 2008 SPIE Astronmical Instrumentation Conference Proceedings, June 23–28, 2008.

[3] W. Williams and W.J. Brown, "Piezoelectric Motor", US Patent, 2439499, April 1948.

[4] T. Morita et al, "An Ultrasonic Micro Motor using a bending transducer based on PZT thin film", Sensors and Actuators A, Vol. 50, pp. 75-80, 1995.

[5] B. Koc, S. Cagatay, K. Uchino, "A piezoelectric motor using two orthogonal bending modes of a hollow cylinder", IEEE Trans. Ultrasonic Ferroelectric Freq. Cont. 49, 495-500, 2002.

BIOGRAPHY

Charles Fisher is a mechanical engineer at the Jet Propulsion Laboratory in Pasadena, CA. He is in the Structures and Configuration group in the Instrument Mechanical Engineering Section. He has designed, integrated, and tested a deployable boom for the Aquarius instrument and has built Ka-Band and L-Band Synthetic Aperture Radars for scientific use on NASA Dryden's Gulfstream III aircraft. He previously worked for the Naval Air Systems Command (NAVAIR) in Patuxent River, MD where he was the lead structural engineer for the EA-6B "Prowler" aircraft and also provided engineering support for the A/V-8B "Harrier" and EA-18G "Growler" aircraft. He has a BSAAE from Purdue University in West Lafayette, IN.

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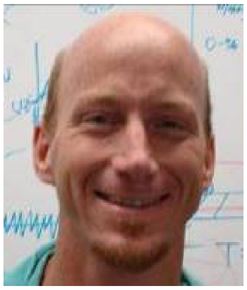

David Braun has 24 years of experience in the Mechanical Systems Division of the Jet Propulsion Laboratory. He has designed and built flight hardware for many projects including major roles delivering structures and mechanisms for the first Mars Rover and subsequent Mars Robotic Arms and Landers. He has also delivered a Siderostat optical assembly with "subatomic" stability and precision pointing systems for the Space Interferometer Mission, and has served on numerous Tiger teams and review boards. He is currently the Group Supervisor for the Opto-Mechanical Engineering Group for the Instrument Mechanical Engineering Section.

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