Sparse Aperture Telescope Active Optics Report

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Abstract Conventional large aperture telescopes required for binary star research are typically cost prohibitive. An automated, sparsely populated aperture design would be an economically feasible solution to expand binary star research. An inexpensive telescope active optics system is needed for sparsely populated apertures to expand binary star research. For this project, a prototype active optics system was created and fitted to a telescope frame using low cost components. The active optics system was capable of tipping, tilting, and elevating the mirrors to align the images of simulated star light. The low cost mirror position actuators are accurate to 31.25 nm, which is accurate enough to perform speckle analysis on red spectrum light. The success of the prototype makes this is a significant step towards a full form, fully automated sparse aperture telescope.

Statement of Problem

Various 4 meter class telescopes have been used to build up observational records of many short-period binaries over the past several decades. However, observing time on 4 meter class telescopes is becoming increasingly difficult to obtain. Our observational record for known binary stars may no longer be able to continue and recently discovered short-period binary stars may receive no observation at all. A dedicated telescope is needed for the observation of binary stars to continue.

Purpose of Study

A dedicated 4 meter class telescope would greatly benefit the observations of close binary stars. Conventional large aperture telescopes required for binary star research are typically cost prohibitive however. An automated telescope with a sparsely populated aperture could be an economic solution to this problem. To align the mirrors of a sparse aperture, an inexpensive active optics system is needed.

Active optics is the technology used to protect a telescope mirror from deformations due to temperature, wind, and structural deflection. In addition, active optics is absolutely essential in the alignment of segmented mirrors for larger telescopes. Active optics should not be confused with adaptive optics however; active optics will not correct atmospheric turbulence or earthquake vibrations.

General Approach

The Sparse Aperture Telescope is meant to be a low cost, high resolution solution to expand the research astronomers can do on Earth. The prototype, seen in Figure 1, measures light through a pinhole, simulating the brightness of binary stars. The telescope mirror is composed of a sparse array of small mirrors, spaced apart to maximize aperture resolution while ensuring desired wavelengths of light are still detectable.

Mirror and Optical Requirements

Speckle analysis requires a surface accuracy roughly one quarter the wavelength measured. This system was designed for 800 nm wavelength light. Therefore, the active optics system needed to be accurate to at least 200 nm. Each mirror needs to be able to travel 1 cm to focus the image. Tip, tilt, and elevation control are required to align segmented mirrors, requiring at least 3 position control points.

The three mirrors were placed to create a 27” aperture. This diameter was chosen to give the best aperture resolution while still allowing for speckle analysis. If the mirrors are spaced too far apart, shorter wavelengths of light can no longer be analyzed using speckle analysis. This mirror spacing was then simulated and found to be valid by Dave Rowe using his speckle simulator and analysis software.

Figure 1. Completed sparse aperture active optics test assembly

Mirror Properties

The three spherical mirrors used for this project were created as a matched set by Hubble Optics. Each mirror has a radius of curvature of 4972 mm, giving a focal ratio of 7.25 with the 27” aperture. Each Pyrex glass mirror is 10.25” in diameter and 25 mm thick, theoretically allowing for simple 3-point support. Each mirror was supported at three evenly spaced points on two-thirds the mirror’s diameter. No whiffletree was used to support the mirror, giving a stiffer design but subject to higher surface error. Finite element analysis (FEA) was used to determine the mirror surface deflection due to gravity was less than 200 nm. As seen in Figure 5, the surface deflects like a trefoil.

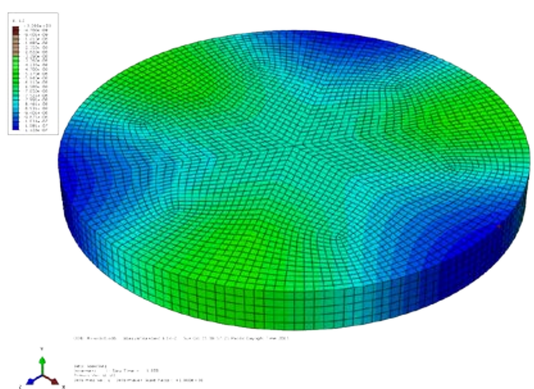

Figure 2. FEA analysis of mirror surface deflection

Mirror Cell Mounting Plate

The mounting plate was made from ¼” plate steel. Three actuators are connected to each mounting plate using two ¼” screws each. These actuators are mounted so that the actuator tip is at two-thirds of the diameter of the mirror. A ½-6” bolt is threaded through the center of the mounting plate to connect the mirror support fixture. This bolt can be adjusted to set the mirror’s minimum height. Each mounting plate has ½” holes through which the plate can be bolted to the mirror support frame.

Mirror Support Frame

The frame has three mounting locations for mirrors. The mirror cell mounting plates bolt to the support frame to ensure a rigid connection. Each mounting plate is fitted to a unique set of mounting holes on the frame. This is due to the thermal expansion caused from welding the frame. This thermal expansion offset the plate mounting position up to 1/8”. The mirror support frame uses a bolt to set it into place on the base of the test frame, preventing movement. Additionally, FEA analysis indicates this support frame should have a first harmonic above 20 Hz, protecting from most common noise factors.

The frame was constructed from steel square tubing because of its high strength and low cost. Additionally, this common steel is simple to machine and weld. The effects of thermal expansion were minimized during welding by a careful distribution of heat during fabrication. Figure 6 shows the final test fitting of the support frame to the telescope base, a critical step before the final welds.

Figure 3. Mirror support frame being fitted to telescope base

Active Optics Actuator

The actuators used in for the active optics system secure to the mirror cell mounting plate by two screws. Using an Arduino with RAMPS board, the actuator is capable of making adjustments of 31.25 nm. Each actuator is also equipped with a limit switch to ensure the mirror cannot collide with the steel housing of the actuator. The actuator consists of a steel housing, limit switch, linear bearing, stepper motor, solid shaft coupling, and a fine adjustment screw. The compact design of the finished set of actuators is seen in Figure 7. These components are protected from dust and other contaminates via an ABS side cover. This actuator design is open loop, utilizing no feedback other than a limit switch.

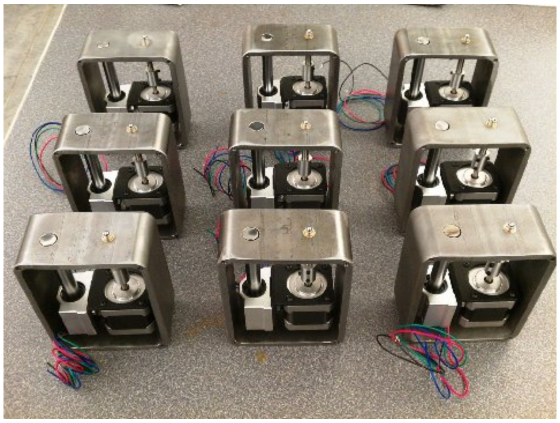

Figure 4. Active optics actuators before attaching side covers

Actuator Housing

The actuator housing is a custom part made from 4” x 5” steel tubing. Holes are drilled into the housing to press fit the shaft for the linear bearing. Another hole is drilled to loose fit the fine adjustment screw bushing. Two tapped holes are located on the bottom for mounting. Each housing has tapped holes on its side to secure plastic side covers. ABS side covers were laser cut to fit the housing. Additionally, holes were laser cut into the ABS side covers to mount the limit switch and to route the stepper motor wires.

Fine Adjustment Screw and Bushing

The actuators used Kozak fine adjustment screws with matched threaded bushings, seen in Figure 8. The adjustor screws are ¼” in diameter with 254 threads per inch. Each screw supports up to 40 lb axially, being primarily limited by its threads. The adjustor screws are made with 303 stainless steel which helps to minimize the risk of part failure due to corrosion. Each adjustor screw is 2” long, but has approximately 2 cm of travel once installed in an actuator. Each fine adjustor screw has a steel ball bearing tip with which it pushes on the back of the mirror. Seen in Figure 9, a sapphire pad is adhered to the back of the mirror surface using Cyanoacrylate. This sapphire pad is used to prevent wear on the mirror and ensures a known, low coefficient of friction.

The adjustor screws operate best in non-condensing conditions. Additionally, the threads are susceptible to dust and dirt and should be covered when not in use. The bronze bushing is self lubricating, meaning this part should not be lubricated. Each threaded bushing is slip fit into its housing and secured with epoxy as recommended by the manufacturer. Due to the tight tolerances of the thread, press fitting the bushings could result in interference. Failure to follow these guidelines could cause the thread to seize.

Figure 5. Kozak 1/4-254 TPI fine adjustment screw

Stepper Motor

The actuators use standard NEMA 17 size stepper motors. This project used commonly available 4-wire, bipolar stepper motors available at reasonable prices from numerous retailers. The motors have a 1.8° step, with 200 steps per full revolution. Each stepper motor is attached to a linear bearing using an aluminum motor mount.

Stepper motors were chosen for their low cost and availability. When paired with a microstepping motor driver, stepper motors can rival the precision of a servo motor at a fraction of the price. They also retain a light holding torque when unpowered, which helps to prevent loss of position when the motor is powered off.

Mirror Support Fixture

The support fixture provides lateral mirror support while allowing vertical actuation. This fixture design uses 0.06” thick ABS, laser cut to the desired geometry. Access to a laser cutter makes this part fast and cheap to produce. This fixture design, using 0.06” thick ABS, is capable of vertical deflection exceeding 2 cm. Furthermore, it limits horizontal deflection to less than 2 mm. A ½” nut is fixed onto the fixture using Cyanoacrylate (super glue) for attachment to the mirror support plate.

Figure 6. Attached mirror support fixture and sapphire pads

Linear Bearing

A linear bearing is used to secure the stepper motor under the fine adjustor screw. Once properly adjusted, the stepper motor is free to travel vertically with minimal rotary backlash. Due to its placement in the assembly, backlash is not a concern. It is because of this reason an inexpensive linear bearing can be used.

Coupler

A solid shaft coupler connects the stepper motor shaft to the fine adjustor screw. A solid coupler ensures minimal torsional deflection. Two set secure the coupler onto a matching shaft, ensuring the matching shaft does not slip even without a milled flat.

Arduino

An Arduino Mega 2560 was used to control each mirror cell. This microcontroller can be programmed using C++ and has an extensive set of preexisting Arduino libraries. The board operates at 16 MHz, allowing plenty of time for motor control and communication protocols. A programming header is also available for the installation of a real time operating system.

Motor Shield

RAMPS 1.4 is a motor shield made popular by 3D printing enthusiasts. The RAMPS board is capable of powering the Arduino board, simplifying project wiring. Each board supports up to 5 stepper drivers. Each motor controller only uses 3 stepper drivers, which leaves room for expansion. The board supports up to 6 limit switches. Basic limit switches require no special hardware because the Arduino MEGA utilizes internal pull-up resistors. An I2C header is available making connecting to the Arduino simple. This allows a large number of Arduino control boards to be deployed and controlled through one control program using I2C protocol. The RAMPS and attached Arduino are powered by a 12V power supply. Higher voltages may damage the connected Arduino, but the RAMPS board can be modified to prevent this.

Each stepper motor is given enough current to ensure no steps are skipped due to friction. If the RAMPS board loses motor power but the Arduino remains powered through USB, the Arduino has no method to detect the loss of motor power. If the Arduino main program tries to send a step command to an unpowered motor driver, the main program will no longer reflect accurate position due to lack of feedback. Because of this, it is important to double check all power connections prior to operation. Alternately, an external pull-up resistor could be used to detect power loss, but was not done for this project.

Stepper Driver

The A4988 motor driver is available on a breakout board made to interface with the RAMPS 1.4 shield. This motor driver is capable of 1/16 microstepping, giving the stepper motors chosen for the project 3200 steps per revolution. With a 254 TPI screw, each motor has a step increment of 31.25 nm. Motor torque can be manually adjusted by increasing the motor current via a potentiometer on each motor driver. Motors can be turned off when not in use, which conserves power and prevents unwanted heat. Powered off motors will not lose their position under normal circumstances, but may be vulnerable to heavy vibration or user handling.

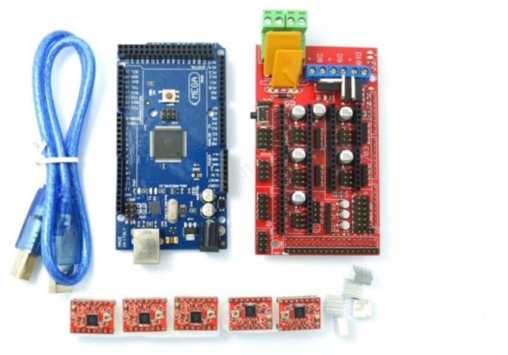

Figure 7. Arduino MEGA (left), RAMPS 1.4 (right), A4988 motor controller (bottom)

Camera

The QHY5L-II M astronomy camera was used for the fine mirror alignment tests. This camera has an internal Barlow of approximately 2.5 times magnification. The camera was mounted to facilitate course adjustment over a range of approximately 2”. This rough adjustment was used to get the mirrors close to focused before using the actuators for fine adjustment.

Light

A green LED with an approximate bandwidth of 10% was used for the fine mirror alignment tests. A 10 um pinhole was placed over this LED to simulate starlight. This light simulates the light power of a binary star, but will only generate one point of light.

Figure 8. QHY5L-II M monochrome astronomy camera

Software

The QHY CCD camera was used with the free software FireCapture. This software allows for exposure and gain control of the QHY, along with a fast capture option for rapid image acquisition.

A custom Arduino control program was written for the actuating the mirrors during these tests. The program is capable of controlling each actuator individually, outputting mirror tip, tilt, and elevation. Communicating with the Arduino control program requires a serial USB connection. Additionally, the Arduino control program uses ANSI escape commands to refresh the display values. The free software PUTTY was chosen to interface with the control program. PUTTY is available for Windows and UNIX systems.

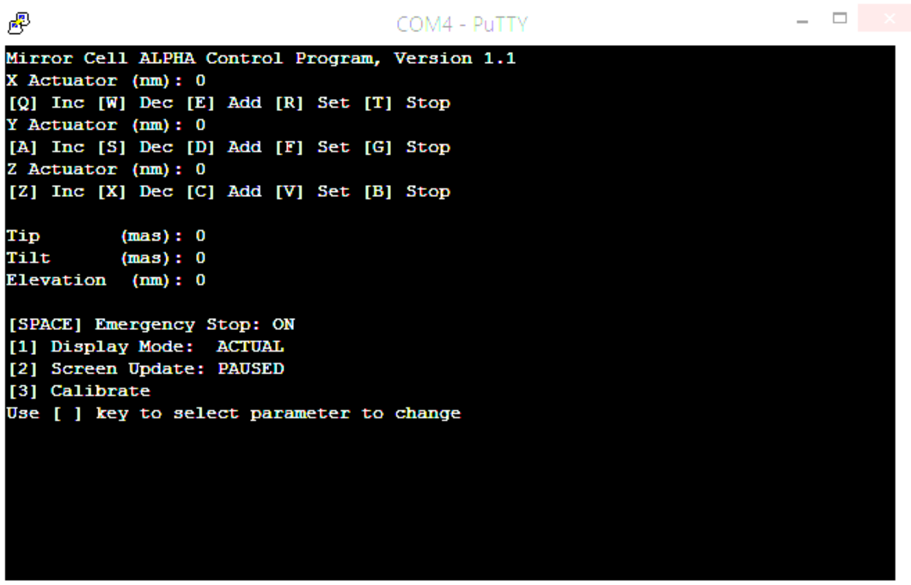

Figure 9. Arduino command program interface through PUTTY

Alternate Rejected Designs

Differential threads were considered in earlier versions of their design, but were later rejected due to susceptibility to backlash, short travel, market availability, and prohibitive cost.

A planetary gearbox was considered for use with a stepper motor as it provides a significant step up in accuracy. Low cost gear boxes have several degrees of backlash however, which would make mirror calibration difficult. Higher precision, low backlash versions were also considered but were highly cost prohibitive.

Voice coils were considered due to their simple construction, accuracy, and travel. They have no backlash and incredible accuracy, some better than 1 um. The downside being voice coils are substantially higher in cost and may not be able to handle the weight of larger mirrors.

Piezo actuators are well suited for astronomy applications. They have no backlash, high accuracy, and can support mirror weight. This unfortunately makes them very expensive, well above the budget for this project. Additionally, piezo actuators often require higher voltages, which could pose a potential safety hazard.

Adjustor Screw Position Testing

A green laser was mounted to the top of the adjustor screw, measuring angular displacement across a known distance. Using an Arduino with a stepper driver, the adjustor was actuated to test for positional error against a target position. As seen in

Figure 13, positional error was found to be within 100 nm of the target. This is due to the backlash of the thread between the adjustor screw and bushing, approximately 180 nm. When the effects of backlash are accommodated for, positional accuracy is within 100 nm. This position can be repeated to within 16 nm.

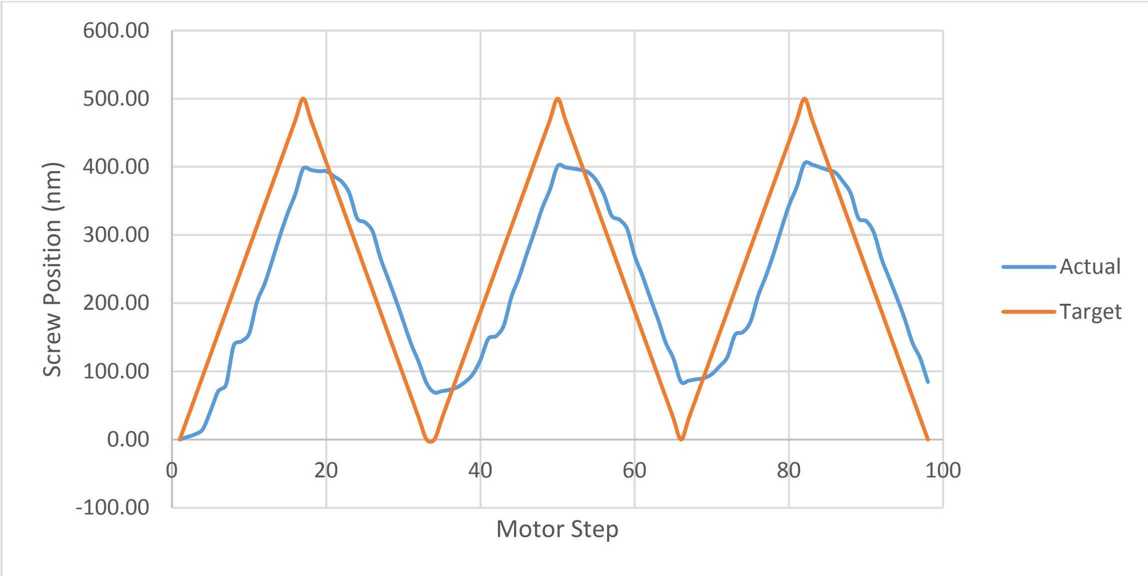

Figure 10. A4988 microstepping test results

Mirror Phasing: Coarse Positioning Testing

The finished sparse mirror array, seen in Figure 14, was tested using a webcam and a bright white LED. To isolate the mirrors, black dust blocking buckets were places on top of the mirrors to block the image. Two mirrors were individually positioned such that the LED circuit was in focus on the webcam, seen in Figure 15. Then, a roughly 100 um pinhole was put onto the LED to simulate a bright star image. Both mirrors were then refocused and aligned to one another. The webcam was limited in that it could not capture an airy disk from the LED. Chromatic aberration and air turbulence were also key factors to the image quality as seen in Figure 16.

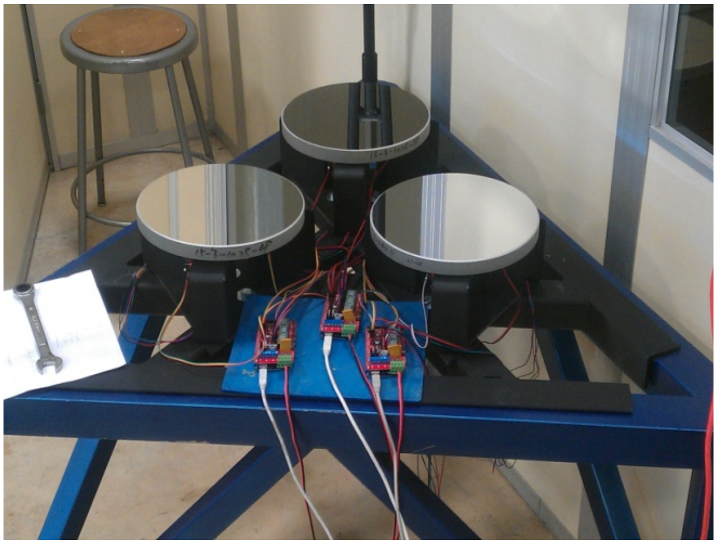

Figure 111. Sparse active optics test setup

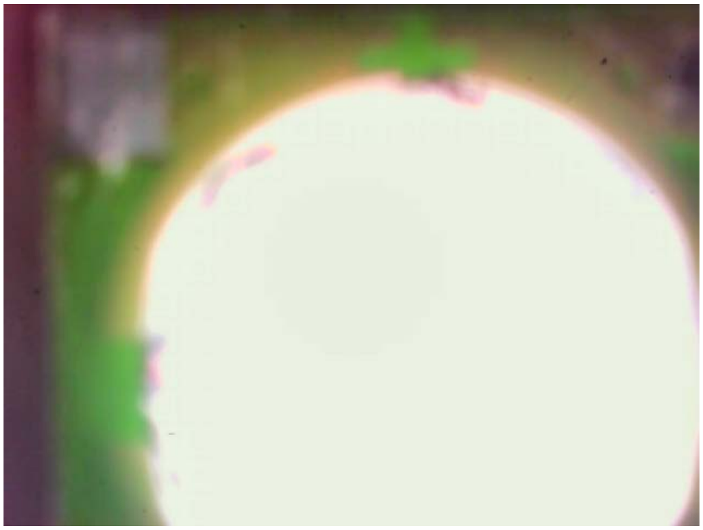

Figure 12. Focused LED circuit with pinhole removed

Figure 13. Webcam capture for alignment mirrors using white LED

Mirror Phasing: Fine Adjustment Testing

The webcam was replaced with a QHY astronomy camera and the large pinhole was replaced with a 10 um ± 1um precision pinhole. The white LED was replaced with a green LED with an approximate bandwidth of 10%. As before, each mirror was setup, focused, and aligned using this new configuration.

During this test, an airy disk was present for each mirror image. However, trefoil aberrations were an issue as seen in Figure 17. Additionally, air turbulence in the room with the trefoil aberrations made it difficult to confirm if the aligned mirrors were able to generate an interference pattern. The overexposed image seen in Figure 18 highlights the detrimental effects from air turbulence. Despite these problems, focusing and aligning the mirrors was successful according to the design goals of this project.

Figure 14. QHY capture for aligned mirrors using green LED

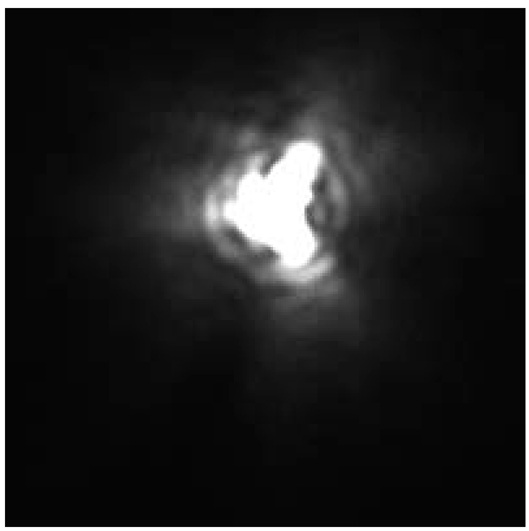

Figure 15. QHY overexposed capture

Contributions to Astronomy

The success of the active optics prototype makes this is a significant step towards sparse aperture telescope. The cost of the active optics components significantly lowers the barrier of entry for large aperture segmented mirror telescopes. This will hopefully contribute to the future development of low-budget telescopes everywhere.

Design Strengths

The active optics actuators are made using low cost parts, offering an economic solution to expensive off the shelf alternatives. With the exception of the actuator housing, each actuator is made from readily available parts. The actuator design is relatively simple, making future maintenance and repair straight forward. If a component fails, it can easily be replaced with simple tools. Assembly requires several wrenches, screw driver, needle nose pliers, a hex key, and Cyanoacrylate (super glue).

Design Weaknesses

Simulation of the mirror deflection indicated a whiffletree should not be needed, but during testing this was proven otherwise. Captured image show trefoil aberrations caused by the simple 3 point support. This trefoil aberration makes detecting an interference pattern challenging.

The actuator housing requires a fair amount of custom machining to make. Without access to tools capable of machining steel, the housing may be costly to reproduce. Some changes to the design need be made to simplify the machining process.

Future Work

A simple, low cost whiffletree is needed before future testing can take place. Ideally, the whiffletree should have a high stiffness with low to no backlash. Alternately, an air filled bag support could be used to “float” the mirror’s weight similar to the WIYN telescope.

The actuator housing would benefit from some minor design changes. The side covers should be attached using another method; this would remove eight tapped holes from the prototype design. Additionally, the mounting holes should be changed. One precision hole should be placed directly under the mounting hole for the fine adjustor screw, with the other mounting hole being less critical. This will ensure a better positional accuracy when mounted to the mirror cell mounting plate. The placement of the matching holes on the mounting plate would need to be adjusted to accommodate for this.

During testing, vibration from the stepper motors was detected when actuating. This vibration was low in amplitude and decayed quickly, posing no serious consequence other than annoyance. This is simple to resolve however, cork NEMA 17 gaskets for reducing vibration are cheap and readily available. These gaskets, while not an urgent necessary, should be included at some point for future testing.

The laser cut ABS mirror support fixture fully satisfied the design requirements for this test setup. If the aperture is pivoted on an angle however, the fixture may not tolerate the weight of the mirror laterally. A thinner fixture made of steel would be needed to support the lateral weight. Additionally, the fixture may need to be redesigned to allow room for a whiffletree.

One actuator experienced 3 times its normal backlash during testing which initially made aligning the images difficult. It was determined this extra backlash was due to a loose bolt holding the stepper motor inside the actuator. Future versions should include a mechanism to prevent this.

Conclusion

The success of the prototype makes this is a significant step towards a full form, fully automated sparse aperture telescope. The active optics system was able to focus and align the mirrors through manual adjustment. Interference patterns could not be found, but this seemed due to a lack of a whiffletree, not because of the positional accuracy of the active optics system. With the addition of image processing, this system has the potential to be completely automated. The components required to build this system are relatively cheap, effective, and will hopefully lead to a fully automated sparse aperture telescope in the future.