Development of a mirror mount suitable for laboratory and OEM applications

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ABSTRACT

Currently a number of manufacturers of opto-mechanical hardware offer mirror mounts that have features incorporated to reduce long term drift and reduce temperature induced mis-alignment. These designs tend to feature kinematic approaches and careful material selection to achieve improved results over prior designs. However, most of these designs still rely on springs and or other preload mechanisms and may not be suitable for harsh environments. In addition, most do not feature a common point of rotation about which the "tip" and "tilt" adjustments are made.

In 2018 a mirror mount design was proposed that attempts to combine the convenience of some of the most common commercially available mounts with the long-term stability and rigidity required of a mount to be used in OEM applications. The proposed mirror mount featured a virtual pivot point, centered on the front surface of the mirror, and incorporated a novel clamping mechanism that allows the mechanism to be fully locked without disturbing the orientation relative to the base. In addition, the mount included features such as a low stress mirror mounting system and a multitude of mounting points to make the mirror mount a versatile option for use in many instances.

This follow-on work explores further applications of the design, shares results and observations from prototyping efforts and discusses the logical next steps in the development of the current and derivative designs.

Keywords: mirror mount, kinematic, alignment, opto-mechanical, gimbal, goniometer, tip/tilt

1. INTRODUCTION

Figure 1. Picture of prototype

The adjustable mirror mount depicted in Figure 1 was designed in an effort to develop a mount that is suitable for OEM applications but retains many of the best features and benefits of off-the-shelf mounts. OEM applications can be far more demanding than lab applications given additional environmental conditions, specifically shock, vibration and temperature fluctuations. These conditions may be present only in shipping or they can exist in operation as well. Often times engineers working on the designs of complex optical instruments will choose to employ custom mirror mounts in order to ensure long-term reliability and stability. However, custom mounts can be costlier and to achieve stability they may sacrifice ease of adjustment. In an effort to overcome these limitations, the following feature list was created to capture the desirable elements for a versatile mount that could be used in both lab and OEM environments[2].

1. Adjustability of at least +/- 3° around orthogonal axis
2. Center of rotation should be located about the nominal reflection point
3. Positive locking mechanism
4. Inherent insensitivity to temperature fluctuations
5. Tool-less adjustment with resolution similar to off-the-shelf offerings
6. Mirror should be located on front surface and be held in a semi-kinematic[1] fashion or with a comparable low-stress approach.
7. Ample and easily accessible surfaces to facilitate stable mounting
8. Compact
9. Economical

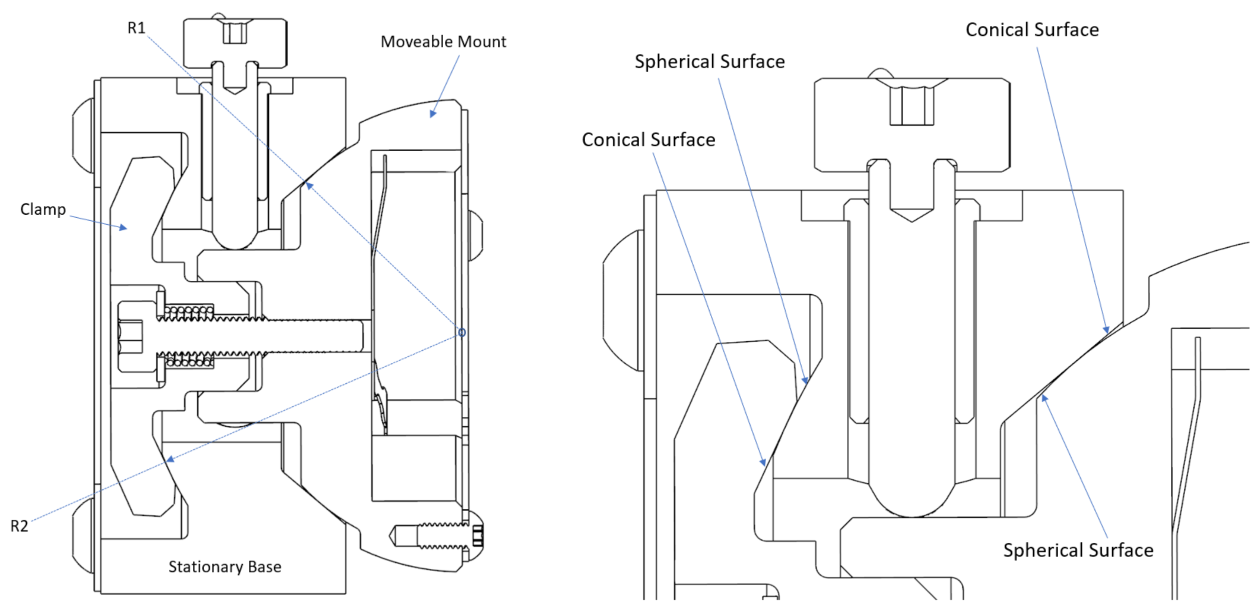
2. THE PROPOSED APPROACH

In the interest of being succinct, not all of the design details that were originally presented in 2018 have been restated here. For a fuller description of the design and functionality please refer to the afore mentioned document[2].

2.1 Guiding Geometry

The mount is based on a spherical interface that consists of a spherical surface contacting a conical surface. If the sphere and the conical surface have perfect form, line contact will exist between the two surfaces. A second spherical interface, concentric with the first, is introduced to provide a means of locking the mechanism directly. The described geometry can be seen in Figures 2a and 2b [2].

Figure 2a shows a cross-section through the adjustable mirror mount first depicted in Figure 1 and Figure 2b shows a magnified view and denotes the spherical and conical surfaces present in the implementation.



Figures 2a and 2b[2]. Cross-section views of the spherical interfaces

Figure 2a shows a central fastener (socket head cap screw) that can be used to clamp the assembly within the stationary portion of the mount. Given that the two spherical interfaces share a common center of rotation (R1 and R2 in Figure 2a), the clamping force does not create a moment to change the pointing of the mount. Underneath the head of the socket head cap screw is a compression spring that serves to provide a preload force. This preload force keeps the moveable mount seated against the conical surface that is integrated into the stationary base. The preload is necessary during adjustment but once in the final position, the structure is locked and the preload is no longer necessary.

To accomplish a controlled adjustment of “tip” and “tilt”, fine pitched actuator screws have been incorporated into the design. It is important to note that the fine pitched actuator screws exert a force perpendicular to an axis of symmetry that would run through the center of rotation of the mirror held within the mount. By orienting the actuator screws normal to the afore mentioned axis, the forces of the screws and their own preload mechanism do not impact the force holding the moveable portion to the stationary base. In this manner the force exerted by the adjustment screws are not working against the clamping force or the preload force of the moveable mount.

2.2 Stability

The mount has been designed to meet the demanding stability requirements of a precision OEM optical system. In the case of the proposed design, stability includes a natural insensitivity to temperature change, long term creep, and or vibration.

Because the clamping mechanism acts on the guiding interface directly the actuator screws are not needed once the final position has been achieved and the position locked. In some cases, it may be beneficial to remove the screws entirely (for reuse elsewhere) or back them off as to prevent the possibility of an over-constrained condition. Once the adjustment screws are disengaged the structural loop consists of the moveable mount, stationary base and clamp. When the design is implemented such that these three parts are made from the same material (or from materials with predominantly similar coefficients of thermal expansion) temperature changes will cause the entire assembly to scale (grow or shrink) but there will be no asymmetric forces that would cause the pointing of the mount to change. The symmetry of the mount leads to an inherently insensitive mechanism.

The mount is also very rigid in its locked state. While many mounts lock the actuator screws, this mount locks the mechanism itself. Fairly high clamping forces can be exerted and once clamped, the assembly behaves as one monolithic part.

3. FURTHER APPLICATIONS AND EXTENSIONS

3.1 Integrated mirror

The design form discussed in this paper lends itself to certain applications and extensions. One such design extension involves the incorporation of the optical surface (typically a mirror) into the movable portion of the mount. Given the relatively simple geometry required to function within the mount it is easily seen that the features that would normally be included in the “moveable mount” can be eliminated in favor of directly forming the mirror surface on to the part itself. This concept is shown in Figure 3. In this figure the mirror surface is approximately 35mm in diameter and could be diamond turned directly onto the substrate. Given the rest of the mount can be made of aluminum this creates and ideal mounting method for the diamond turned mirror. The result is a position-able precision optical surface that can be locked into a stable orientation for long term performance. In addition to plano mirror surfaces, gratings, and even aspheric and other surfaces with optical power could be directly machined into the component.

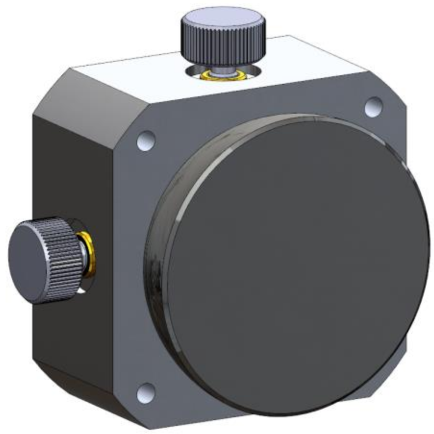


Figure 3. Depiction of mount with integrated mirror

The concept of an integrated mirror can be extended even further by considering glass or ceramic as the material of choice rather than aluminum. In this case a threaded insert could be bonded into a glass or ceramic optic with the suitable geometry on the backside, allowing it to be used directly within the mount.

3.2 Removable actuators

Section 2.2 makes mention of the fact that the actuators are only used when adjusting the angle of the mount and once the mount is locked the actuators are not part of the primary mechanical structure and indeed, they can be removed. This capability presents some unique opportunities that can be taken advantage of in OEM applications.

The simplest extension in this area it to consider the actuators as re-useable from one mount to the next. In an effort to save cost, weight, and complexity, once a mount is positioned, the actuators can be removed and used on the next system to be aligned. In this way the actuators are merely an alignment tool and do not need to be purchased with each mount. A depiction of a mount with the actuators removed is shown in Figure 4.

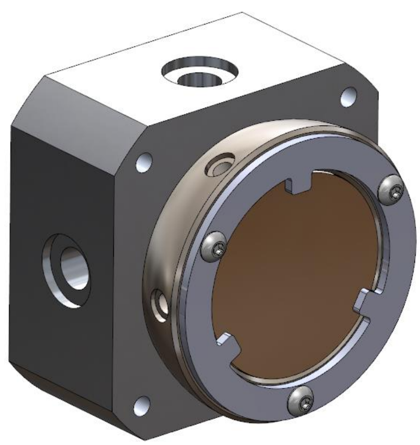
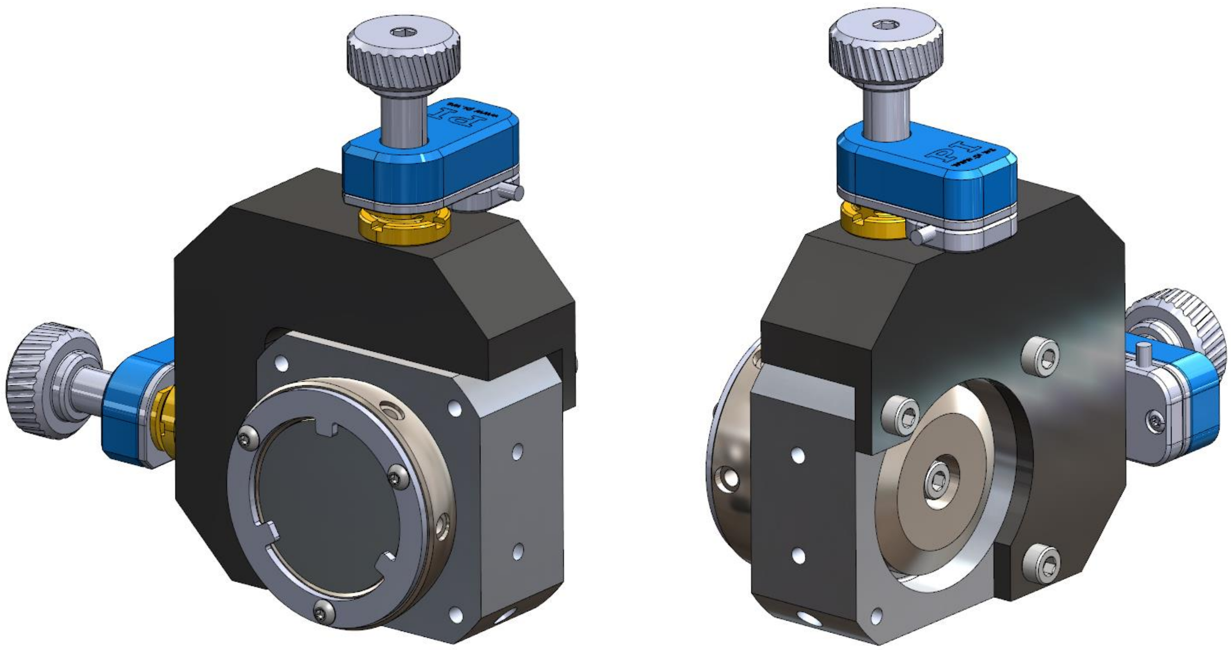


Figure 4. Mirror mount with actuators removed

A more complex application would be to devise a tool equipped with motorized actuators that could be readily attached to a mirror mount with no actuators installed. The motorized actuators could be utilized during the alignment of the product and could even be computer controlled. Once the mirror is in the final position, the mirror mount could be locked and the tool moved to the next mirror mount to be aligned. In this manner, high-resolution actuators can be implemented without adding recurring cost into the system. A concept utilizing piezo inertial drive style actuators from PI[5] is shown in Figure 5.



Figures 5a and 5b. Front and back images of removable tooling concept

4. ASSEMBLY OF PROTOTYPES

4.1 Initial Impressions

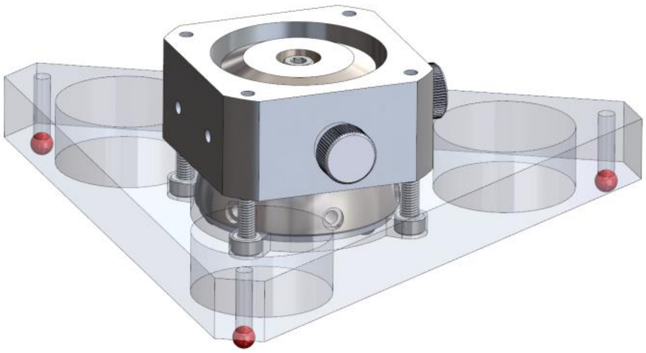
One of the primary concerns regarding the design was the ease with which the spherical surfaces would slide within the mating surfaces, allowing for small adjustments to be made without noticeable “stiction”. It was anticipated that surface finish and the coatings specified on the individual components would play a key role in facilitating a smooth motion.

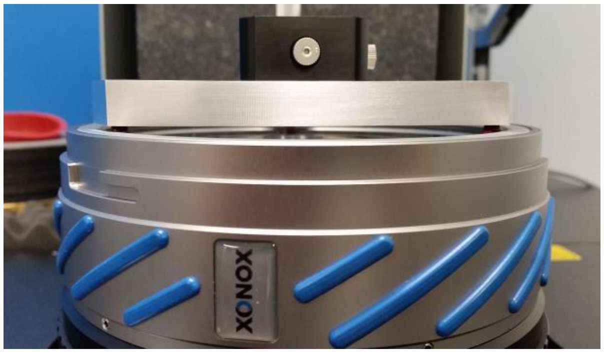
Three prototype assemblies were built in accordance with the original design. Overall the ability to adjust the mirror mounts to a desired location was quite satisfactory. The knobs (see Figure 6) were found to be a little small and it was felt that larger knobs would be more ergonomic.

Figure 6. Image of prototype mount

4.2 Test Setup

Initial testing was conducted by integrating the mirror mount onto a fixture that could be placed directly on the transmission flat of a Fizeau interferometer. The interferometer was part of a XONOX VT1200 workstation which positions the interferometer such that the optical axis is vertical and the beam of the interferometer is exiting upwards. In this position the reference surface of the transmission flat is horizontal and it becomes possible to rest the fixture directly on the transmission flat. Figures 7a and 7b show the described setup.





Figures 7a and 7b. Fixture for placing mirror on interferometer

The result of this setup was a live view of the tilt fringes between the optic held within the mirror mount and the reference surface of the transmission flat. A XONOX "4+" transmission flat was used that has an aperture of approximately 5.2". This aperture allowed for the fixture to have a broad base to improve the stability of the setup. The fixture was made of aluminum to be a match to the material of the mirror mount and the contact points were three precision ruby balls.

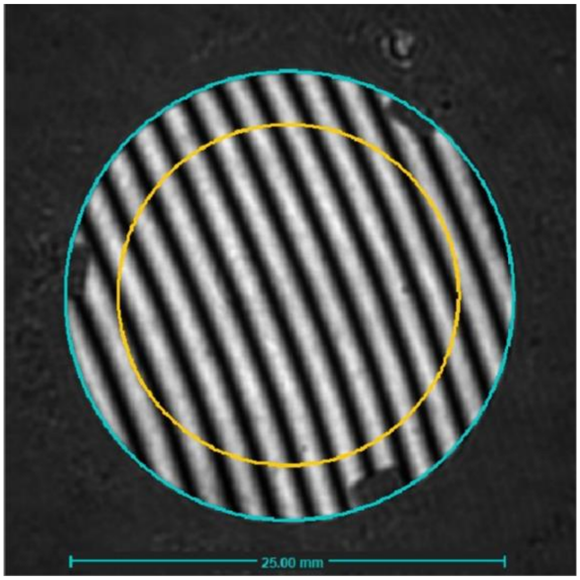


Figure 8. Example of Fringes across test piece

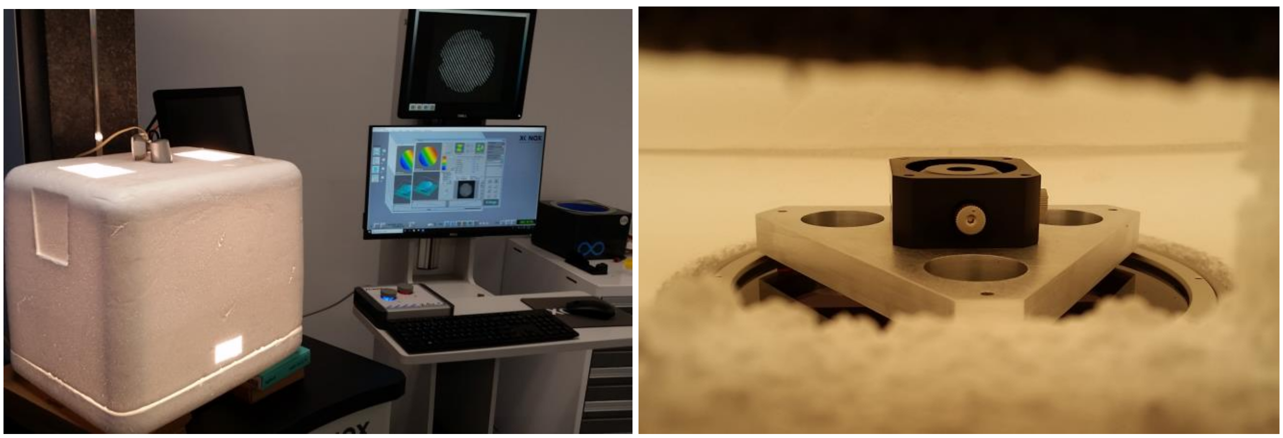
Figure 8 shows an example of the view seen on the interferometer. The three points of the retaining ring can be identified and the outer edge of the optic is visible. Also visible in Figure 7 are two masks. The masks were created within the XONOX *X-Fringe* software and allowed measurements to be made over a known diameter for the calculation of the tilt of the part. Good fringe contrast was achieved by using an optical element that was plano on one side and had a long radius on the opposite side. The part was uncoated and therefore suitable to be used with a standard transmission flat. The radiused second surface helped to avoid issues with backside interference.

To test the ability of making fine adjustments the goal was to null out as many fringes as possible. It was straightforward to repeatably achieve less than one fringe across the part which correlates to an ability to set the angle to within 12 µrad of the desired value. When conducting the tests, stiction related effects were not found to be significant; rather it was the ability to rotate the actuator screws the fractional amounts necessary for small movements that seemed to limit the resolution. Larger knobs, finer thread pitch or the use of a tool could address this and improve the ability to make small adjustments.

5. TEMPERATURE TESTING

5.1 Description of Test

A review of published data for commercially available mirror mounts[6] revealed that best-in-class mounts were achieving stabilities on the order of 0.5 µrad per degree of thermal drift and hysteresis values on the order of 1 µrad after exposure to 10+ deg C of temperature change. In order to measure changes in pointing on this scale a thermal chamber was devised that could be placed directly over the mount while resting on the transmission flat. In this way, interferometry could be used as a means to measure slight angle changes of the mount as the temperature was raised and lowered.



Figures 9a and 9b. Images outside and inside the thermal chamber

The thermal chamber was fashioned from a Styrofoam cooler (see Figures 9a and 9b). What was intended to be the lid became the base and a hole was cut just large enough to fit around the circumference of the transmission flat. The heat source was an incandescent light bulb placed inside the box near the top and a sheet of aluminum foil was suspended between the source and the mirror mount to reduce direct radiant heating. Two vents were cut in the top of the box and sized such that a reasonable steady state temperature would be reached with a 40W bulb operating continuously. A small window was cut in one side of the box to allow measurements to be taken with an infrared thermometer. It was later found that the window's presence on one side created a small temperature asymmetry in the chamber and had a negative effect on the results. Due to this finding the window was sealed for the test runs that follow.

Given the mount was attached to a fixture resting directly on the reference flat, phase shifting interferometry was not possible as the mirror under test moved directly with the reference surface. This was easily overcome by utilizing the static fringe mode within the XONOX *X-Fringe* software. To facilitate accurate static fringe measurements, it is recommended that there be about 15 fringes covering the measurement aperture. When this condition was met the repeatability of the measurement was tested. The 2-sigma value for measurement of tilt relative to the reference flat was found to be an excellent 0.12 µrad and the measurement approach was dreamed appropriate for characterization of the mount to the levels required.

5.2 Results from thermal tests

The data in Figure 10 plots the results from the first run after the assembly of the optic into the mount, assembly of the mount to the fixture, adjustment of the angle of the mount using the actuator screws and finally locking the mount. The metals of the optical mount had not been thermally cycled previously.

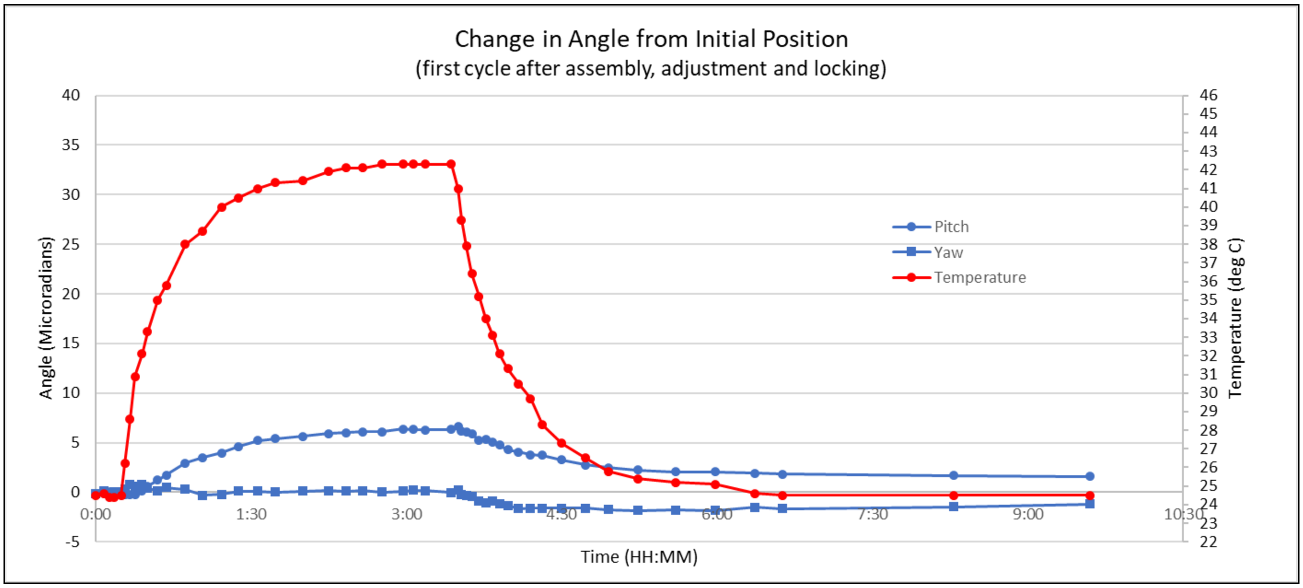


Figure 10. Results from thermal testing

Temperature data was taken with an infrared thermometer aimed at the locking clamp of the mount through one of the vents in the top of the chamber. When the mount temperature and the angle reached a stable position at the elevated temperature the total change in angle (magnitude) was 6.6 µrad. This change was for a temperature rise of 17.3 degrees C, or 0.38 µrad / deg C. 6 hours after the heat source was turned off the change in angle (magnitude) from the initial conditions was 2.0 µrad (shown on graph) and 12 hours later the value had reduced to 1.2 µrad (not shown on graph)

Without making any adjustments the same assembly was subjected to a second temperature cycle, see Figure 11.

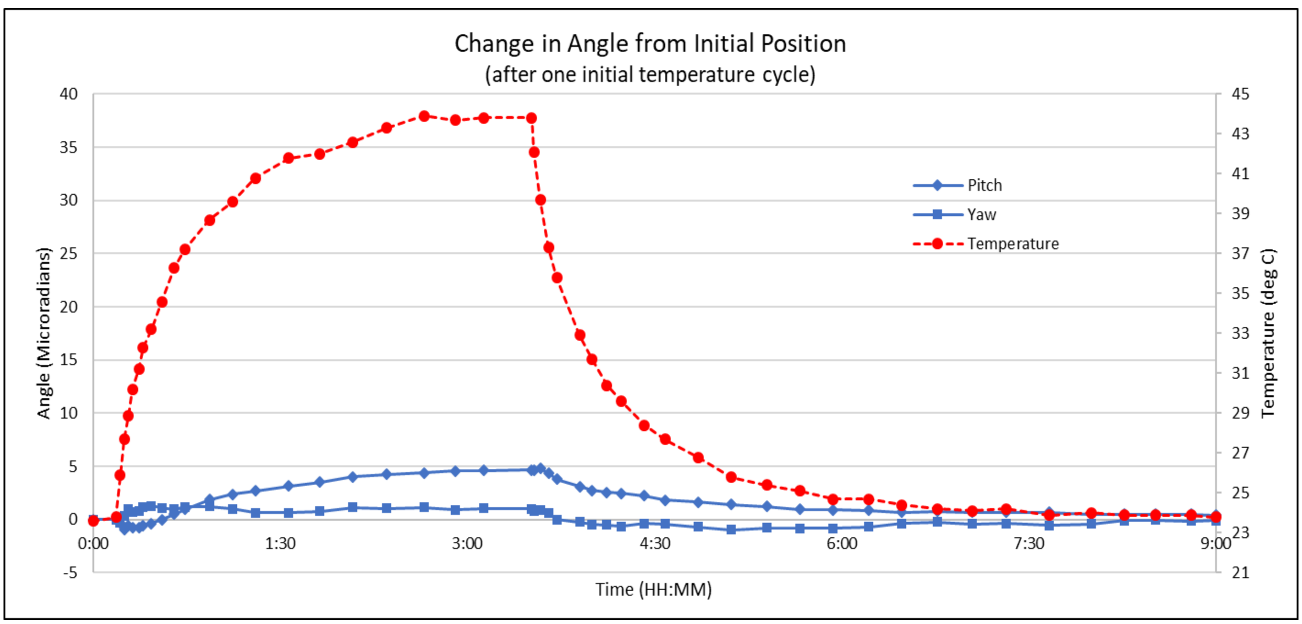


Figure 11. Results from repeated thermal test

When the mount temperature and the angle reached a stable position at the elevated temperature the total change in angle (magnitude) was 4.9 µrad. This change was for a change in mount temperature of 20.0 degrees C, or 0.25 µrad / deg C. 5.5 hours after the heat source was turned off the change in angle (magnitude) from the initial conditions was 0.4 µrad (shown on graph) and 12 hours later the value had reduced to 0.1 μrad (not shown on graph). A summary of the results can be seen in Figure 12.

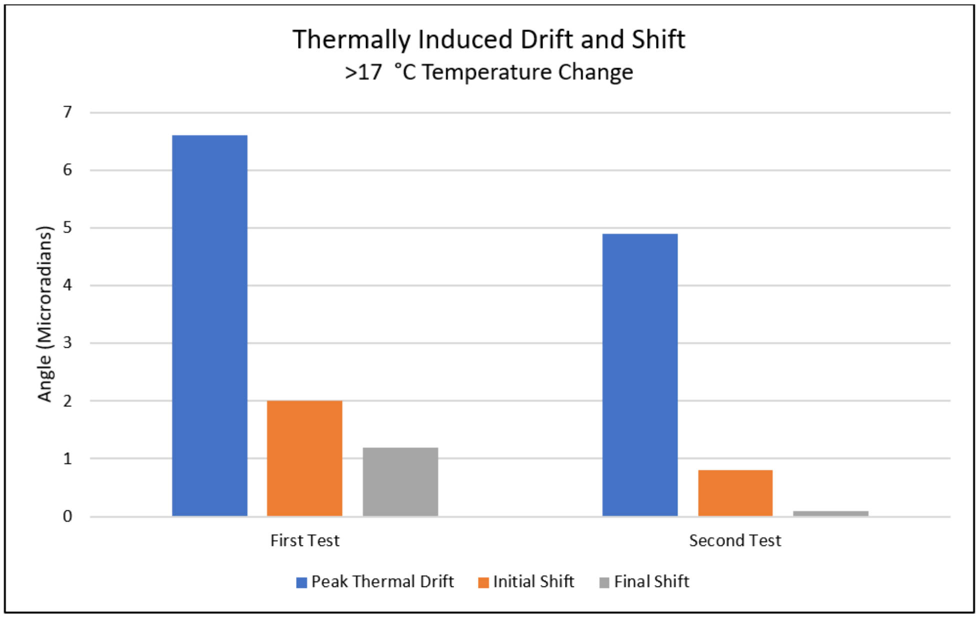


Figure 12. Thermal Testing Results Summary

5.3 Thoughts and interpretations of the results shown

It is not surprising that an initial, unrecovered shift occurred as a result of the first temperature cycle of the mirror. Imperfect geometry and the effects of friction can result in unbalanced stresses within the structure as the components are clamped together. The cycling of the temperature can result in a new equilibrium being found and therefore a shift from the initial position. It is not clear if all of the shift was a result from the clamping of the mount or if there was some contribution from the fact that the optical element had been freshly inserted and the mount itself had just been attached to the fixture. More testing is required to determine the sources of the small thermal shift that occurred.

The stability exhibited during the second cycle was very encouraging. The mount showed almost no permanent shift in pointing as a result of the cycle (though it's a bit surprising just how long it takes the mount to return to the final position). Due to constraints of the test it is unknown just how quickly the mount returned to the final value of 0.1 μrad; it is only known that 12 hours later, that was the result.

Both tests showed larger shifts in the "Pitch" direction. There is no clear asymmetry between the "pitch" and "yaw" directions in the mount so there is no clear mechanical mechanism for the difference. The strongest hypothesis at this time is that the shift in angle was higher in the "pitch" direction because of a non-uniform distribution of temperatures within the thermal chamber. The mount was closer to the back of the box than the front and therefore not centered relative to the heat source. Without a fan to "mix" the internal air it's probable that the mount and fixture were slightly hotter on one side versus the other and this resulted in the majority of the temperature dependent pointing that was exhibited. This direction of the offset relative to the heat source is consistent with the direction that showed a higher change in angle.

Though it is likely that the results can be further improved with optimization of the test conditions, the performance already exhibited shows the design to be capable of performance on par with the best-in-class mounts currently available.

6. DESIGN UPDATES

Prior to the manufacturing of more units, the following design updates have been addressed and implemented.

6.1 Ergonomics and Economics

The ergonomics of the mount were improved by increasing the diameter of the knobs and they were made to extend further away from the mount. In an interest to keep the mount compact the increases are not drastic. Given that the actuator screws are easily customized, the chosen values are meant to be a good starting point but may be optimized for a given application.

A second change that was made was primarily cosmetic. The initial design concept depicted a cover plate on the back of the mount. It was decided that this cover offered no significant advantage and to save cost and open up more mounting possibilities, it was eliminated.

6.2 Mirror Mounting

The initial design concept assumed a stainless-steel face plate that would provide the three datum points on which the optical surface of the mirror would rest. In addition, there was a preload spring (also made of stainless steel) that was located behind the mirror to press the mirror against the datum points. Initial testing with a stainless-steel face plate indicated that the mismatch of the coefficients of thermal expansion between the stainless-steel and the aluminum "moveable mount" portion of the structure created an instability when exposed to changing temperatures. To rectify this, the material was changed to aluminum and the thickness increased to makeup for the stiffness lost in the material change.

A second change in the design was the addition of radial M3x0.5 holes around the perimeter of the "moveable mount". These holes can be used to retain or position a part radially with M3 set screws or the holes can be used for the injection of an elastomeric compound as an alternative means to mount an optic into the mount.

The final change to the design was to the preload spring that resides behind the mirror. The initial concept had relatively short flexure arms that resulted in a very short useable stroke and therefore would accommodate only small thickness variations in the optic being mounted. Finite Element Analysis was used to develop a geometry that would provide a longer stroke before material yield. The resulting design can be seen in the figure below.

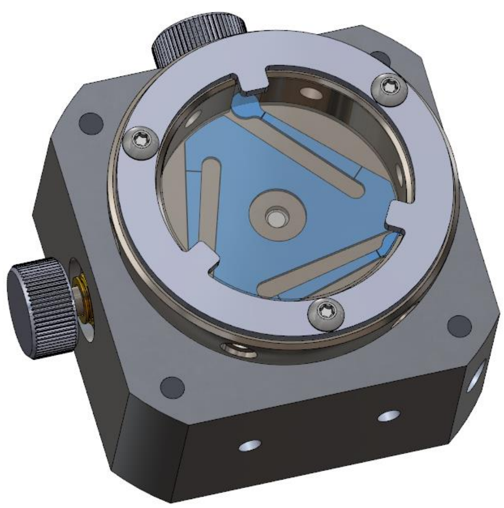


Figure 13. View of preload spring located behind mirror

7. NEXT STEPS IN DEVELOPMENT

7.1 Repeat thermal testing

Given the hypothesis that one of the primary contributors to the temperature dependent pointing was non-uniform temperatures within the thermal chamber (and therefore within the mount), it is desirable to address the shortcoming of the test setup and repeat the test. A repeat test could help to confirm the hypothesis or show that there is a different explanation.

7.2 Quantify stability of the mount when exposed to vibration and shock

The positive locking mechanism is anticipated to provide excellent stability in the presence of shock and vibration. It is desirable to conduct some practical "handling" tests to demonstrate the mount's stability when subjected to environments that could be experienced in shipping. However, to conduct such tests, a reliable means of measuring the movement of the optical surface relative to the mounting features of the mount needs to be devised. While the tests that were done with the fixture on the interferometer have demonstrated good repeatability (even when removing the fixture from the transmission flat and then putting it back in place), the clocking of the fixture on the transmission flat was not controlled other than visually. This was not an issue for temperature testing because the fixture did not need to be removed, and therefore results could always be compared to initial conditions. However, when checking the effects of shock and vibration, a method would need to be devised to ensure that the fixture can placed back in the exact same location on the transmission flat so that any changes in pointing can be adequately captured.

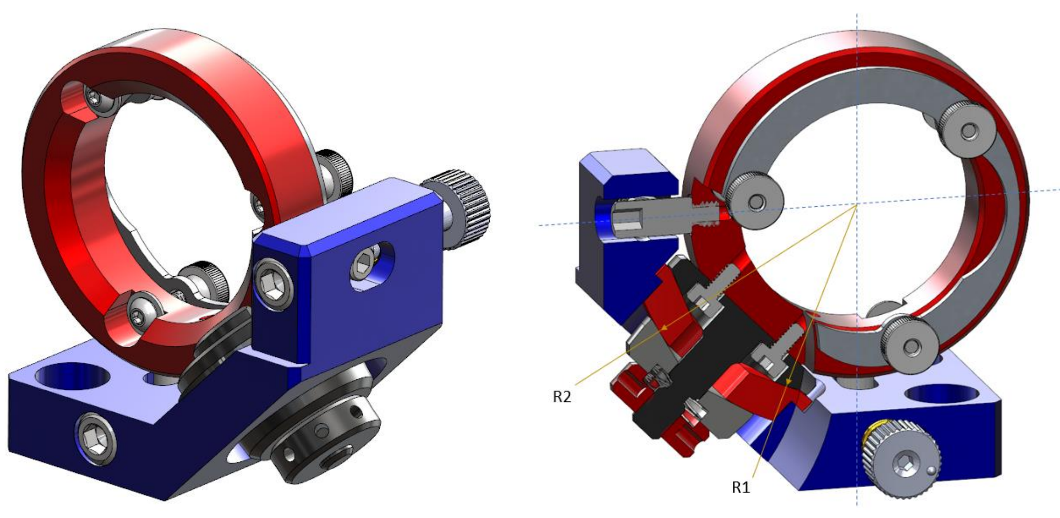
7.3 Optimization of locking interfaces

In initial testing it was found that when locking the mount, a measurable change in angle was induced as the mount was locked. The shift was repeatable and it was demonstrated that it could be compensated for by dialing in an offset before locking, such that as the mount is locked it comes to the desired position. While this practice is commonplace in optical alignments it is desirable to explore options to reduce the effect.

It is believed that the behavior comes from imperfect geometry or the fit of the mating parts that guide the axial motion of the clamp relative to the moveable mount. The geometry concerns could be addressed by introducing a semi-kinematic interface where the sphere acts on three small defined areas to make the final position more predictable. Likewise, the clamp can use a similar geometry and the tolerances that guide the clamp relative to the moveable mount can be revisited.

7.4 Prototyping of derivative designs

The prototyped mirror mount was the first step in the development of a series of mounts based on the concentric spherical guiding geometry and spherical clamping mechanism. This patent pending approach has been shown to be applicable to other styles of optical mounts such as the mount shown in Figures 14a and 14b below.



Figures 14a and 14[2]. Detailed views of derivative design

Though the layout of this mount (suitable for beam splitters and/or other transmissive elements) is quite different from the prototyped mirror mount, the details of the design and the operation are based on the same principles.

The two concentric spherical surfaces can be seen in Figure 14b. R1 serves as the guiding interface and establishes the location of the optic in X, Y and Z. Rotations around the vertical and horizontal axis are constrained and adjusted by the fine pitched screws that reside on those orthogonal planes. Finally, rotation about the axis of the mounting ring for the optic is controlled by how the pins (that the actuators act on) are constrained within their slots. This mount also benefits from the same capability of being able to completely remove the actuators once locked; creating a stable structure defined by only one material type.

In addition, the mount has been carefully designed to maximize the clear aperture when used at a 45-degree angle as to optimize it for applications of beam splitting and beam combining. The 1-inch (25.4mm) mount shown above can pass a 13mm diameter beam at a 45-degree angle.

8. SUMMARY

The testing of the prototype mirror mounts has confirmed the design to have favorable performance characteristics. Hands on experience has demonstrated that the mount is convenient to use and the temperature testing has proved the mounts ability to maintain consistent pointing in the presence of large temperature swings. These results combined with the key features that were included in the design such as rotation around the point of reflection, compact size, multiple mounting options, and low stress mirror mounting make for a feature rich mirror mount.

In addition to the results gained from the current embodiment of the mirror mount, the options for an integrated mirror, removable actuators (or tooling) and further forms that will address transmissive optics, all point to a versatile approach that can provide a solution to a variety of optical alignment challenges.

9. ACKNOWLEDGMENTS

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