ThermoYield Actuators: Nano-Adjustable Set-and-Forget Optics Mounts

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ABSTRACT

The X-ray optics community has been developing technology for high angular resolution, large collecting area X-ray telescopes such as the Lynx X-ray telescope concept. To meet the high collecting area requirements of such telescope concepts, research is being conducted on thin, segmented optics. The mounts that fixture and align segmented optics must be the correct length to sub-micron accuracy to satisfy the angular resolution goals of such a concept. Set-and-forget adjustable length optical mounting posts have been developed to meet this need. The actuator consists of a cylinder made of metal. Halfway up the height of the metal cylinder, a reduced diameter cylindrical neck is cut. To change the length of this actuator, an axial compressive or tensile force is applied to the actuator. A high-current electrical pulse is sent through the actuator, and this electrical current resistively heats the neck of the actuator. This heating temporarily reduces the yield strength of the neck, so that the applied force plastically deforms the neck. Once the current stops and the neck cools, the neck will regain yield strength, and the plastic deformation will stop. All of the plastic deformation that occurred during heating is now permanent. Both compression and expansion of these actuators has been demonstrated in steps ranging from 6 nanometers to several microns. This paper will explain the concept of ThermoYield actuation, explore X-ray telescope applications, describe an experimental setup, show and discuss data, and propose future ideas.

Keywords: Adjustable, Set-and-Forget, X-ray telescope, Segmented optics, X-ray mirror, Optical mount

1. INTRODUCTION

This paper describes the operating principle of ThermoYield actuators, which are nano-adjustable set-and-forget optical mounts. The concept is to make a cylinder out of metal, and apply a constant axial force in either compression or tension. That force causes a stress in the cylinder below the yield strength, so that no permanent deformation of the cylinder occurs. Next, the metal cylinder is quickly heated via resistive heating from a pulse of electrical current, which temporarily reduces its yield strength. With enough heat, the yield strength will fall below the applied stress caused by the constant force. When this happens, the metal cylinder will start plastically deforming. Once the heat source is removed and the cylinder cools, the metal will regain its yield strength and stop plastically deforming. At this point, the constant force can be removed. The plastic deformation that occurred during heating has permanently changed the length of the metal cylinder. This is the operating principle of ThermoYield actuators. In the past, Bruccoleri et al. had used a powerful laser to heat a layer of solder in a process called liquid metal actuation[1]. Electrical heating in ThermoYield actuation has the benefits of heating the entire volume of the material instead of just the surface, delivering the heat further away from the mirrors, being cheaper, working with opaque materials, and being safer for operators.

In practice, the metal cylinder described in this process is a necked-down section of a larger metal cylinder. The larger cylinder doesn't participate in the process and is only added for mounting. A diagram of this process is shown in Figure 1.

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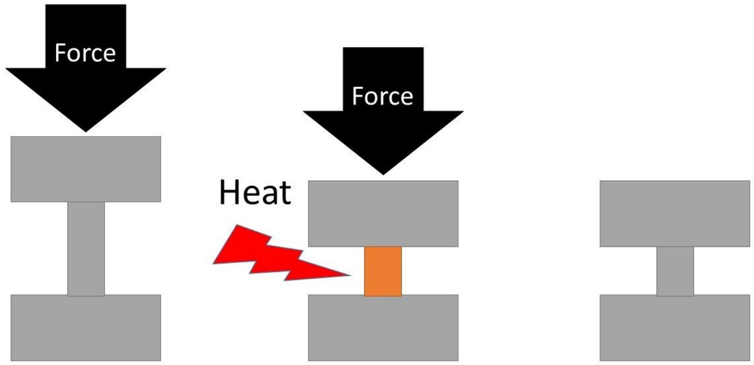

Figure 1. Conceptual drawing of ThermoYield actuation. First, the sample is compressed, causing a stress in the neck of the sample. Next, the neck is quickly heated, which temporarily reduces its strength. The applied force then plastically deforms the neck. When the neck cools, it regains strength and stops deforming. The sample is now permanently shorter. The top and bottom of the sample do not participate in the process.

The target application of ThermoYield actuators is the precision alignment and mounting of thin-shell X-ray telescope mirrors. The idea of using thin segmented optics for X-ray telescope construction has already been demonstrated by the NuSTAR X-ray telescope. The NuSTAR X-ray telescope was constructed by stacking thin slumped-glass mirrors on top of each other in layers, using graphite spacers between each layer[2]. NuSTAR achieved a large effective area using this technique[3], however its angular resolution was fairly low, around 50 arcseconds HPD[4]. At present, the X-ray astronomy optics community is working towards the Lynx X-ray telescope mission concept with greater than two square meter effective collecting area and angular resolution of 0.5 arcseconds HPD[5].

In order to meet these ambitious collecting area and angular resolution requirements, several different approaches are being researched to build X-ray telescope optics and assemblies. One particularly promising approach is the meta-shell approach described in detail by McClelland et al[6]. In the meta-shell concept, a radially symmetric mandrel is mounted on a precision spindle. This allows the mandrel to rotate about the optical axis. Then, four small posts are epoxied to the mandrel. Next, the posts are precision machined to the correct height and a thin monocrystalline silicon mirror is epoxied to the top of the posts. The mandrel is rotated and this process is repeated until mirrors are attached around the entire perimeter of the mandrel. After the first layer is complete, a second layer is added on top of the first layer using the same procedure. This stacking is repeated until tens of layers are constructed. Finally, several of these meta-shell assemblies will be concentrically nested and aligned to produce a large X-ray telescope focusing optic.

ThermoYield actuators are designed to serve as the four posts supporting each silicon mirror segment. The height of meta-shell mirror mounting posts must be controlled to sub-micron accuracy[7]. ThermoYield actuators have demonstrated the necessary accuracy, down to 6 nanometer steps. Additionally, ThermoYield actuators could change length even with mirrors attached to both sides. This might allow a mirror to be adjusted under real-time metrology, even after epoxy bonding. Additionally, a Lynx-size X-ray telescope will require thousands of mirrors, thus requiring cheap, easy-to-manufacture posts. ThermoYield actuators should be inexpensive and easy to manufacture, since they are a simple, homogenous metal part.

2. EXPERIMENTAL SETUP

2.1 Experimental apparatus construction

In order to demonstrate and evaluate the ThermoYield actuator concept, an experimental apparatus was built. The apparatus measured the length changes of a ThermoYield actuator with a noise floor of around 2 nanometers. It also recorded the force applied to the actuator, and the amount of energy delivered in the electrical heating pulse. The apparatus fixed one end of the ThermoYield actuator to an optical breadboard and constrained the other end of the actuator to only move axially using an optical stage. A capacitive displacement sensor was rigidly mounted to the moving end of the sample, and measured against a micrometer rigidly attached to the fixed end of the sample. The micrometer was not used to measure the length change of the sample, instead it was used as the capacitive displacement sensor grounded target so that the capacitive displacement sensor's air gap could be adjusted. A constant compressive or tensile force was applied to the sample using springs. One end of the spring attached to the moving end of the sample, and the other end of the spring attached to a load cell. The load cell was then attached to an optical stage. That optical stage was attached to the optical breadboard. Finally, high-current electrical clamps were connected to the apparatus on each side of the sample. Since the breadboard has a thick, non-conductive black coating, all of the current from the capacitor bank must pass through the sample. A labeled picture of this apparatus is presented in Figure 2.

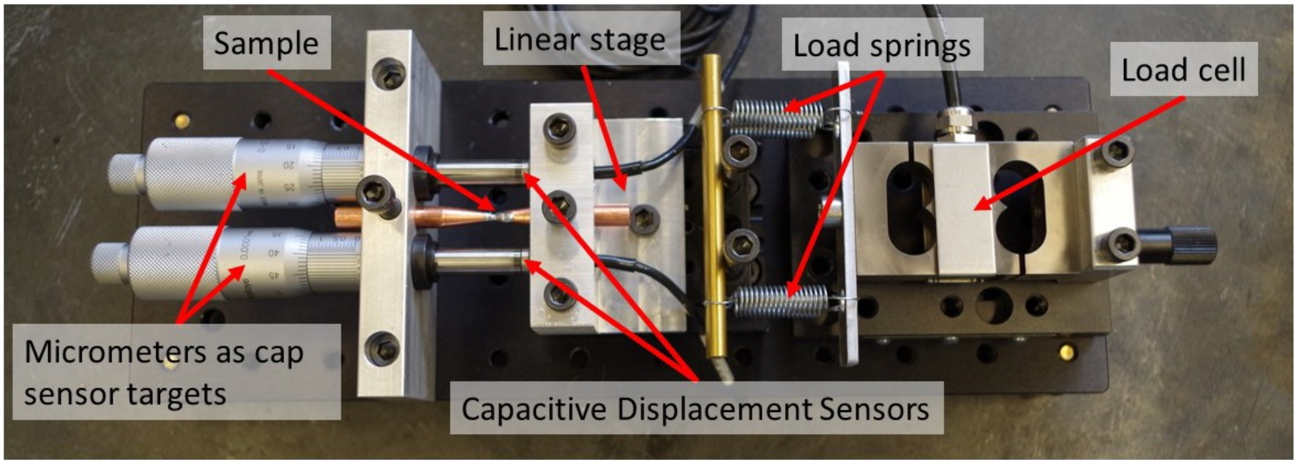

Figure 2. Initial experimental apparatus. Gaps of several microns exist between the capacitive displacement sensors and the micrometers.

Several changes were made to this experimental apparatus. The first modification was the pre-loading of the micrometers using springs. Pre-loading the micrometer made sure the backlash of the micrometer was eliminated and ensured a stable target for the capacitive displacement sensor. Another change made to the apparatus was the removal of one of the capacitive displacement sensors. Having more than one capacitive displacement sensor introduced interference between the sensors and increased the noise floor. In preliminary tests, both capacitive displacement sensors read similar displacements, so using two was redundant. Using only one capacitive displacement sensor without interference produced better measurements. A picture of the apparatus with a pre-loaded micrometer and one capacitive displacement sensor is shown in Figure 3.

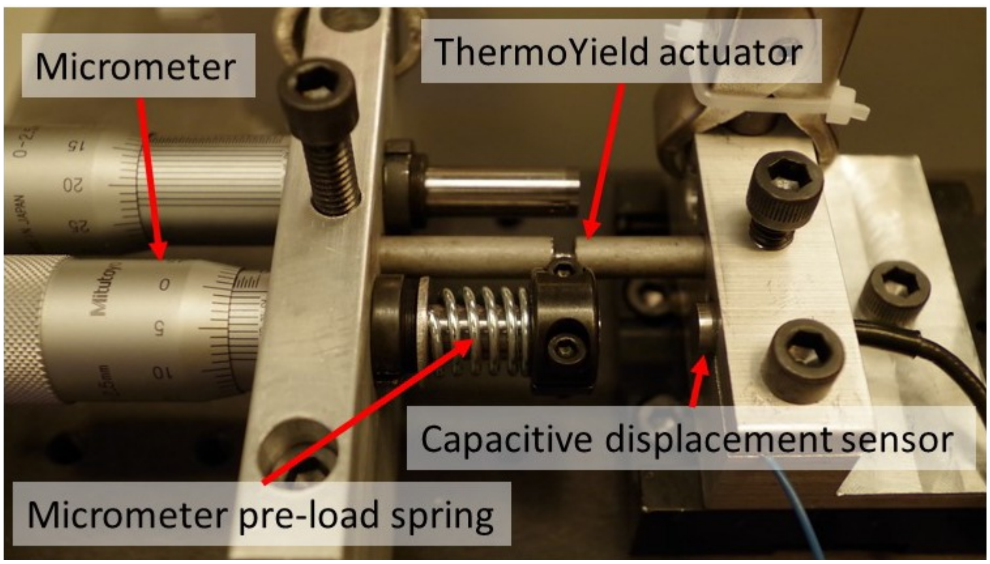

Figure 3. The micrometer has been pre-loaded using a spring. Only one capacitive displacement sensor is used. The gap between the capacitive displacement sensor and the micrometer is exaggerated for demonstration; the gap is usually on the order of tens of microns.

Finally, there was a possibility that the roller-bearing optical stage may have been stick-slipping, so it was replaced with a flexure stage. The flexure stage was pushed using the load cell to make sure the flexure stage stiffness wouldn't significantly influence the force measurements. The flexure stage measured to be several orders of magnitude less stiff than the samples, so its force contribution was ignored. The flexure stage produced data almost identical to the roller-bearing stage, so it was likely unnecessary. A picture of the flexure stage installed in the apparatus is shown in Figure 4.

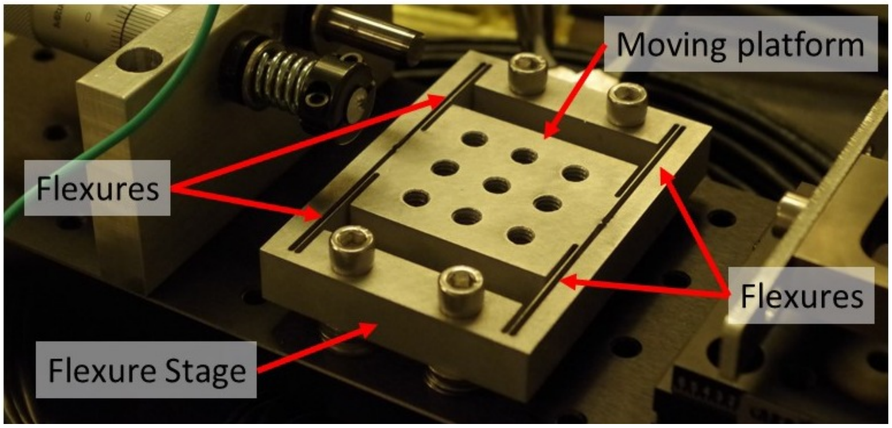

Figure 4. The roller-bearing stage has been replaced by a flexure stage to eliminate the possibility of stick-slip of the stage influencing measurements. In this image the sample holder and capacitive displacement sensors have been removed.

2.2 Experimental apparatus electronics

A 0.2 Farad 200V max capacitor bank was built using 10 large electrolytic capacitors in parallel. For the switch, a SCR with a 46,000 amp for 1 millisecond current rating was used. The SCR was triggered by a 9V battery on a momentary switch, passed through an isolated pulse transformer. The system was built into a metal case, and charged using a 160V 5 amp adjustable bench supply. Note that the capacitor bank can be charged to any voltage between 0V and 160V, allowing significant flexibility in how much energy could be delivered to the sample. A picture of the electrical system is shown in Figure 5.

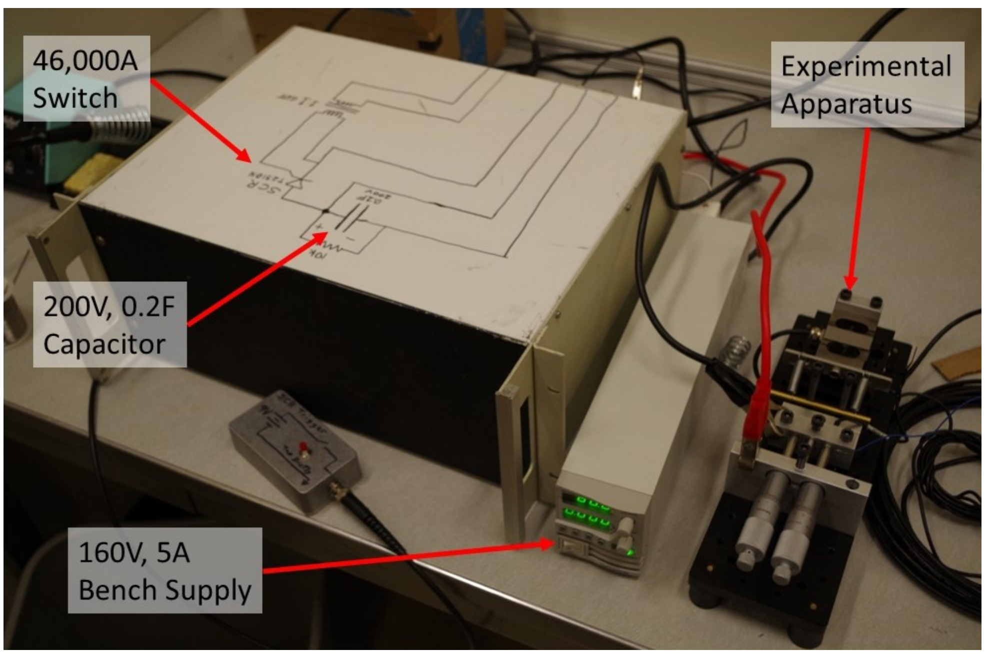

Figure 5. The capacitor bank and switch used to deliver current pulses are housed inside of a metal box.

2.3 Experimental Sample

A test ThermoYield actuator was machined out of FN381, an iron-nickel alloy with a coefficient of thermal expansion similar to that of silicon. It is desirable to match the CTE to silicon since these ThermoYield actuators will be in contact with silicon mirrors. As a result the difference in CTE between the post and the mirror could cause distortions in the mirror when the temperature changes. A cylinder made of FN381 was machined to 6.35 millimeters in diameter and roughly 52 millimeters long. Next, a roughly cylindrical neck was ground into the middle of the sample. The neck was 0.86 millimeters in diameter and 1.12 millimeters long. Notice that only the neck of the sample participates in ThermoYield actuaton, so the dimensions of the rest of the sample aren't critical. This sample was installed in the ThermoYield apparatus.

3. EXPERIMENTAL PROCEDURE AND DATA

The ThermoYield actuator made of FN381 was loaded into the experimental apparatus and left in a ±1 degree C cleanroom overnight to reach thermal equilibrium. During the experiment, the apparatus was covered with a plastic container to further prevent changes in temperature. The amount of force applied to the ThermoYield actuator was determined by slowly increasing the force on the actuator by moving the load cell's optical stage until the ThermoYield actuator started creeping approximately 5 nanometers every 100 seconds, then backing off until the rate of creep was lower than the 2 nanometer noise floor. This procedure resulted in a compressive stress of 42.6 megapascals in the actuator neck. Once the actuator was under load, the capacitor bank was charged to a low voltage and discharged through the actuator. Often, the actuator didn't measurably change length on the first discharge, so the capacitor bank voltage was repeatedly increased and discharged through the actuator until actuations over 50 nanometers occurred. The change in length of the sample, the applied force, and the voltage on the capacitor bank were all recorded. Several actuations were recorded in the same sitting, at the same applied force and capacitor bank voltage. Next, the capacitor bank voltage was increased, and more actuations were recorded. Finally, the capacitor bank voltage was decreased, and several actuations were recorded. Figure 6 shows data for the FN381 ThermoYield actuator (described in section 2.3) actuating under compressive load. Each blue dot represents the change in length of the sample caused by one capacitor bank discharge. Each orange square represents the amount of energy stored in the capacitor bank immediately before discharging. Note that much of the energy from the capacitor bank is dissipated in the resistance of the wires and doesn't contribute to the sample heating. Therefore the energies plotted should be viewed as relative values. The force applied to the sample was held constant during this experiment. All actuations were done in the same sitting, without touching the apparatus, with approximately 100 seconds between each actuation. The data from this experiment is shown in Figure 6.

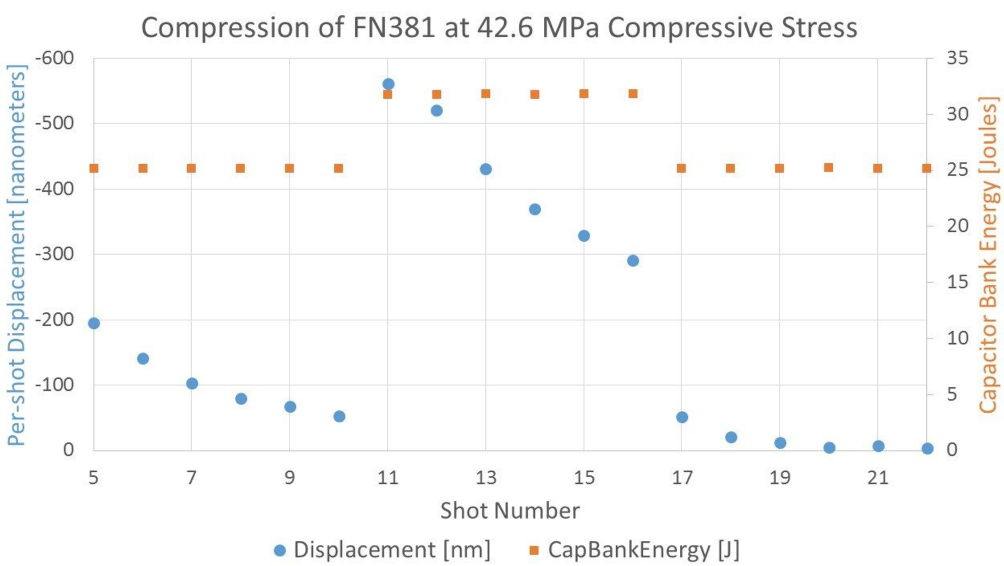

Figure 6. Data gathered using the experimental procedure described in Section 3.

After the experiment from Figure 6, the compression spring was removed from the apparatus and the ThermoYield actuator was under negligible load. The capacitor bank was charged to the same energy that was used in the end of the previous experiment and discharged through the unloaded actuator. This unloaded-actuator discharge was repeated several times. The data from this procedure is shown in Figure 7.

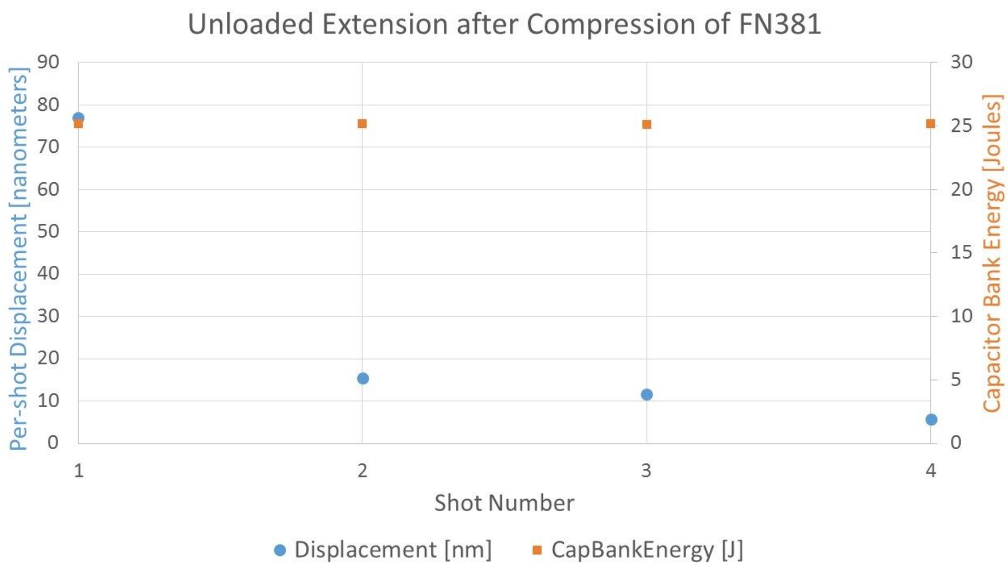

Figure 7. Data gathered with no applied force on the sample. This experiment was performed immediately after the compressive actuations in Figure 6. Notice these actuations are in the opposite direction of the ones in Figure 6.

The sample was then put under tensile load. The same procedure that was used for the compressive load experiment was used for finding the amount of tensile load to apply. The same procedure of doing multiple actuations at different capacitor bank energies was also used. In addition to those experiments, much smaller capacitor bank voltage increases and decreases were also tested. The data for those actuations is shown in Figure 8.

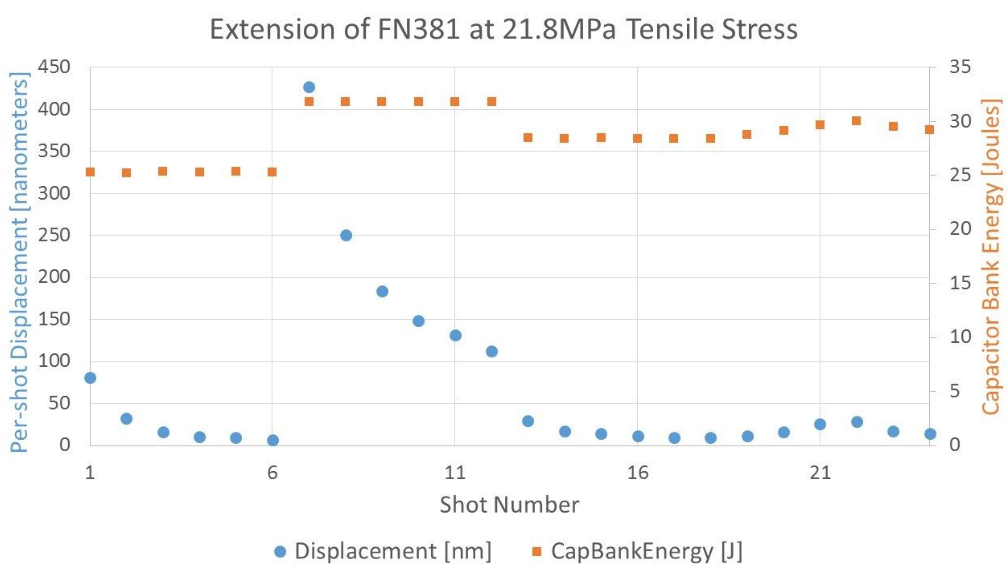

Figure 8. Data gathered with sample under tensile stress. Notice the small increases and decreases in capacitor bank voltage result in small increases and decreases in actuation displacement.

Finally, the tensile load springs were removed from the apparatus and the sample was under negligible load. The capacitor bank was charged to a higher voltage than was used in Figure 8 and discharged through the sample several times, and the resulting displacements were measured. That data is shown in Figure 9.

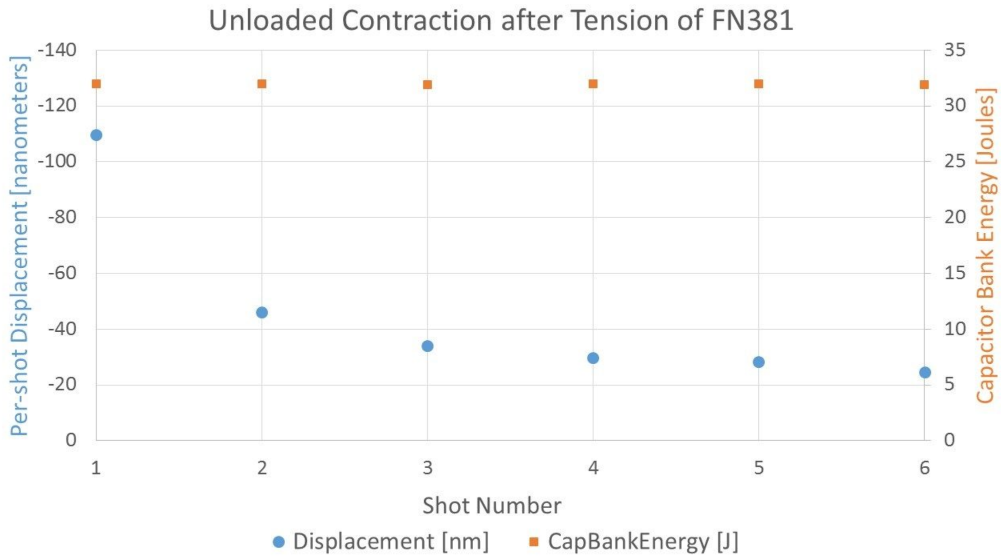

Figure 9. Data gathered with no applied force on the sample. This experiment was performed immediately after the tensile actuations in Figure 8. Notice these actuations are in the opposite direction of the ones in Figure 8.

4. DISCUSSION

This data shows several important features of ThermoYield actuators. First, ThermoYield actuators were demonstrated to achieve actuations as small as 6 nanometers in both compression and tension. This corresponds to a 0.025 arc-second angle adjustment on a mirror supported by 50 millimeter spaced actuators. This exceeds the necessary resolution to align mirrors for a 0.5 arc-second mission such as the Lynx X-ray telescope concept. Additionally, the cumulative displacement in each direction is on the order of micrometers, enabling us to start with relatively coarsely made posts and actuate to the desired length.

Second, the data demonstrates that changing the energy stored in the capacitor bank changes the size of the actuations. This allows the displacement of actuations to be changed without disturbing the precision assembly, a potentially useful feature. The capacitor bank can be mounted remotely, with energy transferred through long wires. It may even be possible to put a precision assembly in a vacuum chamber or x-ray beamline, and actuate the actuators through an electrical feed-through. It also demonstrates that small changes in the energy stored in the capacitor bank can be used to fine-tune the displacement of subsequent actuations and carefully approach a desired length. Large actuations can be used at the beginning to achieve coarse adjustment, and fine actuations can be used later to achieve an exact final length.

Finally, ThermoYield actuators were observed to have "memory" of past actuations. In each trial, the energy and force applied to the actuator were held constant for several actuations; however, each subsequent actuation decreased in displacement. This is noteworthy, since predicting the displacement of the next actuation may depend on the entire history of the sample. The decreasing displacement of subsequent actuations can be overcome by simply increasing the energy used to heat the sample. The effect of the sample's memory was observed when the sample was unloaded of external force. Each time the sample was unloaded of external force and the capacitor bank discharged through it, the sample moved the opposite direction of the most recent actuations.

This memory actuation with no external force could be a useful feature. It should be possible to actuate these samples during the manufacturing process, then install them into a system. Once they are installed, they can be actuated with no applied force using this memory actuation. This may be especially useful in thin-shell X-ray telescope fabrication, since the actuators may be actuated with the mirror installed. This would allow for real-time metrology, or possibly even real-time X-ray data, without distorting the mirror with an external force.

5. CONCLUSION

In this paper, the concept of ThermoYield actuators is presented as well as its utility for aligning X-ray optics in applications such as the Lynx X-ray telescope concept. Preliminary data is presented via a testing apparatus, and several features of the data are discussed. Length changes as small as 6 nanometers were demonstrated in both compression and extension. Cumulative length changes on the order of microns were demonstrated in both directions. A promising idea of using the unloaded "memory" actuations to adjust thin-shell X-ray telescope mirrors was discussed. This work is ongoing, with several current experiments and future goals. Currently, several different materials, such as aluminum, brass, and tungsten have been successfully actuated and are being explored. Smaller and more compact actuators are being fabricated and tested. Furthermore electrical connections for the small gap between mirrors are being designed and built. In the near future, actuators made of poly-silicon may be tested, and experiments on the long-term stability of these mounts will be explored.

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REFERENCES

[1] Bruccoleri, A. R., Klingensmith, M., Chalifoux, B., Heilmann, R. K., Schattenburg, M. L., "Liquid metal actuators: correctable mounting and assembly of thin-shell x-ray telescope mirrors," Proc. SPIE 9603, Optics for EUV, X-Ray, and Gamma-Ray Astronomy VII, 960312 (4 September 2015);

[2] Koglin, J. E., An, H., Blaedel, K. L., Brejnholt, N.F., Christensen, F. E., Craig, W. W., Decker, T. A., Hailey, C. J., Hale, L. C., Harrison, F. A., Jensen, C. P., Madsen, K. K., Mori, K., Pivovaroff, M. J., Tajiri, G., Zhang, W. W., "NuSTAR hard x-ray optics design and performance," Proc. SPIE 7437, Optics for EUV, X-Ray, and Gamma-Ray Astronomy IV, 74370C (2009);

[3] Brejnholt, N. F., Christensen, F. E., Westergaard, N. J., Hailey, C. J., Koglin, J. E., Craig, W. W., "NuSTAR on-ground calibration: II. Effective area," Proc. SPIE 8443, Space Telescopes and Instrumentation 2012: Ultraviolet to Gamma Ray, 84431Y (2012);

[4] Westergaard, N. J., Madsen, K. K., Brejnholt, N. F., Koglin, J. E., Christensen, F. E., Pivovaroff, M. J., Vogel, J. K., "NuSTAR on-ground calibration: I. Imaging quality," Proc. SPIE 8443, Space Telescopes and Instrumentation 2012: Ultraviolet to Gamma Ray, 84431X (2012);

[5] Gaskin, J. A., Weisskopf, M. C., Vikhlinin, A., Tananbaum, H. D., Bandler, S. R., Bautz, M. W., Burrows, D. N., Falcone, A. D., Harrison, F. A., Heilmann, R. K., Heinz, S., Hopkins, R. C., Kilbourne, C. A., Kouveliotou, C., Kraft, R. P., Kravtsov, A. V., McEntaffer, R. L., Natarajan, P., O'Dell, S. L., Petre, R., Prieskorn, Z. R., Ptak, A. F., Ramsey, B. D., Reid, P. B., Schnell, A. R., Schwartz, D. A., Townsley, L. K., "The X-ray Surveyor Mission: a concept study," Proc. SPIE 9601, UV, X-Ray, and Gamma-Ray Space Instrumentation for Astronomy XIX, 96010J (2015);

[6] McClelland, R. S., Bonafede, J. A., Saha, T. T., Solly, P. M., Zhang, W. W., "Design and analysis of an x-ray mirror assembly using the meta-shell approach," Proc. SPIE 9905, Space Telescopes and Instrumentation 2016: Ultraviolet to Gamma Ray, 99057A (2016);

[7] Chan, K., Zhang, W. W., Schofield, M. J., Numata, A., Mazzarella, J. R., Saha, T. T., Biskach, M. P., McClelland, R. S., Niemeyer, J., Sharpe, M. V., Olsen, L. G., "Alignment and distortion-free integration of lightweight mirrors into meta-shells for high-resolution astronomical x-ray optics," Proc. SPIE 9905, Space Telescopes and Instrumentation 2016: Ultraviolet to Gamma Ray, 99056X (2016);