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Heejoo Choi, Marcos A. Esparza, Ariel Lamdan, Yi-Ting Feng, Tom Milster, Daniel Apai, Dae Wook Kim, "In-process metrology for segmented optics UV curing control," Proc. SPIE 11487, Optical Manufacturing and Testing XIII, 114870M (20 August 2020); doi: 10.1117/12.2569310

SPIE.

Event: SPIE Optical Engineering + Applications, 2020, Online Only

In-process metrology for segmented optics UV curing control

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ABSTRACT

Powerful and novel telescope design is key to pushing the available limits of astronomical sciences and a segmented primary is an attractive approach. For the Nautilus Space mission, a segmented lens has been proposed to replace large monolithic primary optics for the purpose of survey faint objects like exo-planets as well as time-domain astrophysics observations. Enabling technology for Nautilus is an ultra-lightweight multi-order diffractive engineered (MODE) lens that replaces bulky primary mirrors. The MODE lens consists of multiple, identical, molded segments. This is because the complicated optical design of both the diffractive surfaces is not easily manufacturable by traditional fabrication methods. Besides, the molding approach for identical segmented optics allows for a cost-efficient process. Conversely, the fusion of segmented optics demands high precision metrology and a delicate assembly strategy. We propose an in-process metrology technique that mitigates post-assembly process complications. This system monitors the co-phase character of the segmented optics during UV cured assembly, guiding the overall process.

Keywords: Metrology, in-process metrology, wide dynamic range and high precision test, multi-segmented optics

1 INTRODUCTION

The large diameter aperture of telescope in visible-near IR observation is a key parameter that determines spatial resolution as well as the amount of light collected from the object under observation. Large telescope fabrication, especially in space missions, has been developing slowly due to the difficult processes of fabrication, alignment, and launch. Our team proposed the Nautilus Observatory, which uses an array of telescope units possessing significantly large apertures while maintaining a realizable, effective, cost[1, 2]. Each unit telescope is optimized to provide a very large collecting area while maintaining a low cost and high fairing space efficiency. Each telescope is launched in a compact configuration and uses a spherical inflatable structure (Fig. 1) when it reaches target orbit (sun-earth L2 point). The specially developed MODE lens focuses the light on the NAVIIS (Nautilus Visual Infrared Imaging Spectrograph) which implements imaging and low-resolution spectroscopy in the spectral range of 0.5 – 1.7 microns. The vertically compact launch configuration allows multiple deploys simultaneously (Fig. 1), and the 50 m telescope is realized by two rocket launches (NASA SLSB2, 25 units per rocket).

To construct the compact inflatable telescope units, our team has been developing the MODE lens which is both thin and light but does not compromise optical performance. The MODE lens has multiple diffractive surfaces, high harmonics orders (M=1000+), and multiple zones. These features are able to compress the chromatic error and generate a relatively short focal length that is an inherent limitation of previous diffractive optics missions (e.g., Eyeglass[3, 4] and MOIRE[5] project).

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Optical Manufacturing and Testing XIII, edited by Dae Wook Kim, Rolf Rascher,
Proc. of SPIE Vol. 11487, 114870M · © 2020 SPIE · CCC code:
0277-786X/20/$21 · doi: 10.1117/12.2569310

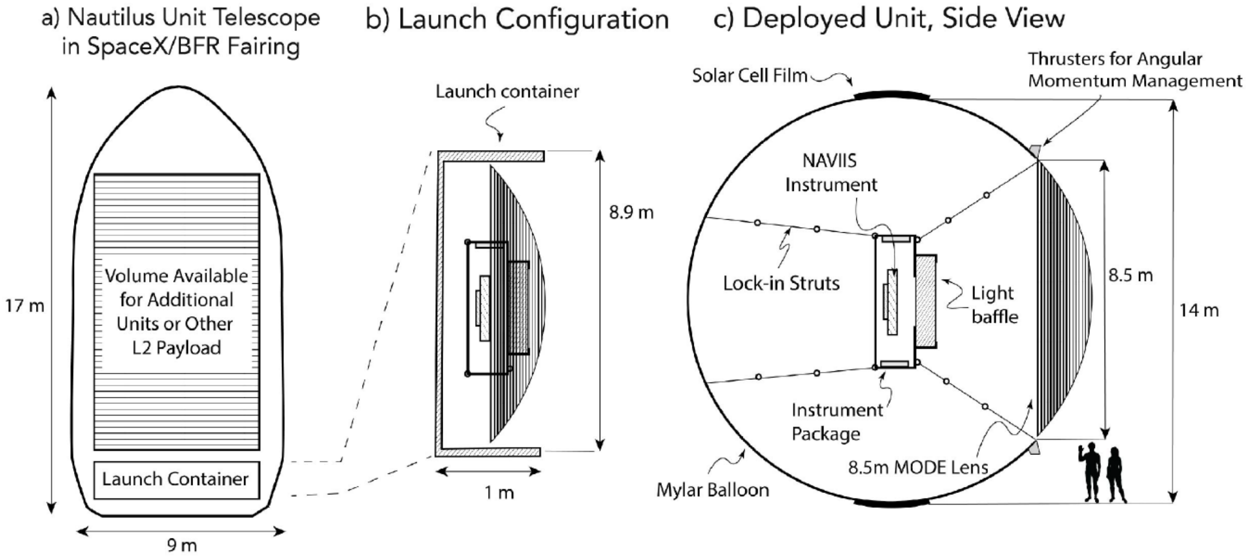

Figure 1. Conceptual image of the Nautilus telescope launch configuration and deployed unit[1]. The vertically thin container could be stacked 25 units in the fairing space.

The advantages of the MODE lens consist of efficient weight, space, and cost managing and localization of the fabrication process, as well as an improved tolerance to misalignment when compared to reflective optics[6]. The intricate optical surface of the MODE lens could not be achieved via traditional fabrication methods. To achieve the surface complexity required by the diffractive optics, fine control of a diamond turning cutting tool and glass molding methods appear to be most promising. However, because the desired MODE lens diameter for space missions is larger than the size of available molding and diamond turning machines, the segmented approach will be used to make the MODE lenses. In Fig 2, the segments along the perimeter have an identical surface figuring due to the axially symmetrical design. Indeed, only a single mold set is required for eight segment fabrication and it makes an identical surface shape optic while reducing fabrication cost.

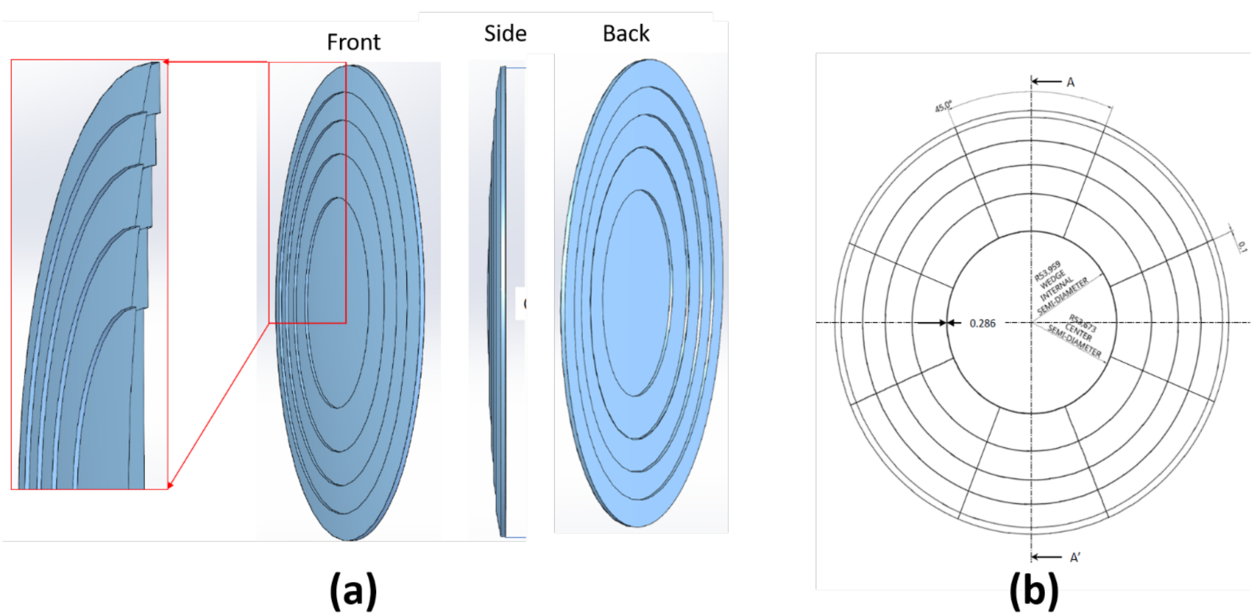

Figure 2. Prototyping optical design of a MODE lens. (a) The front surface is a multi-order diffraction design, and the back surface is a diffractive Fresnel lens. (The fine structure of the DFL is not present due to the scale.) (b) Mechanical drawing for machining. Mode lens is made of 8 identical segments at the perimeter, and one circular piece at center.

This segmented approach has been adopted in various large optics fabrication projects, especially space missions, to utilize large aperture primary optics. However, the co-phasing and/or fusion process to achieve monolithic optic performance requires high precision metrology and orientation control. Even though the MODE design has a large tolerance on misalignment during assembly, proper control of the assembly and bonding process is still required to ensure optimal performance of the telescope. The Kinematically Engaged Yoke System (KEYS) is developed to align and hold the segments in their co-phased position. In this paper, we present the high precision metrology technique that is implemented in-process.

In Section. 2, the fundamental of the metrology are described, and the overall control procedure is shown in Section 3. In Section 4 and 5, the results of the metrology and curing process are presented.

2 IN-PROCESS METROLOGY TECHNIQUE

For the precision measuring of alignment, we propose an in-process metrology technique using multiplexed pattern deflectometry. During the UV curing process, all segments should keep their co-phased position and any position drifting caused by gravitation, thermal elongation, and UV curing stress needs to be monitored and handled properly. In order to measure and guide the curing process, the metrology technique is required to have large dynamic range, high accuracy, and instantaneous multi-segments measuring capability.

At the first stage of alignment, each component might be far away from its final aligned and co-phased position. This wide dynamic range ensures the measuring of the entire process from the first coarse arrangement to the final fine co-phasing alignment of each segment. In another scenario, an auxiliary instrument (e.g., interferometer and profilometer) may be used for the co-phasing step. After fine alignment is done, the orientation of this step must be measured so that the metrology system can make a comparison while curing. The wide dynamic range of this process enables the measurement of all segments in any scenario. During UV curing, any small drift from initial co-phasing status is measured and fed to the system which is then adjusted to avoid inappropriate fusion.

We developed the simultaneous multi-segmented mirror orientation test system[7, 8] (Fig. 3(a)). This system layout is shown in Fig 3. The camera images the pattern on the reflected monitor screen through the unit under test (UUT). Initial images of the pattern reflecting off the UUT surfaces (Fig. 3 (b)) are taken at the first iteration. Then, the metrology system continuously compares the refreshed image against the initial images. The variation of the UUT orientation induces a linearly shifted sinusoidal pattern in the captured images. The tilted angle is extracted using FFT sheared pattern analysis[7, 8] as follows.

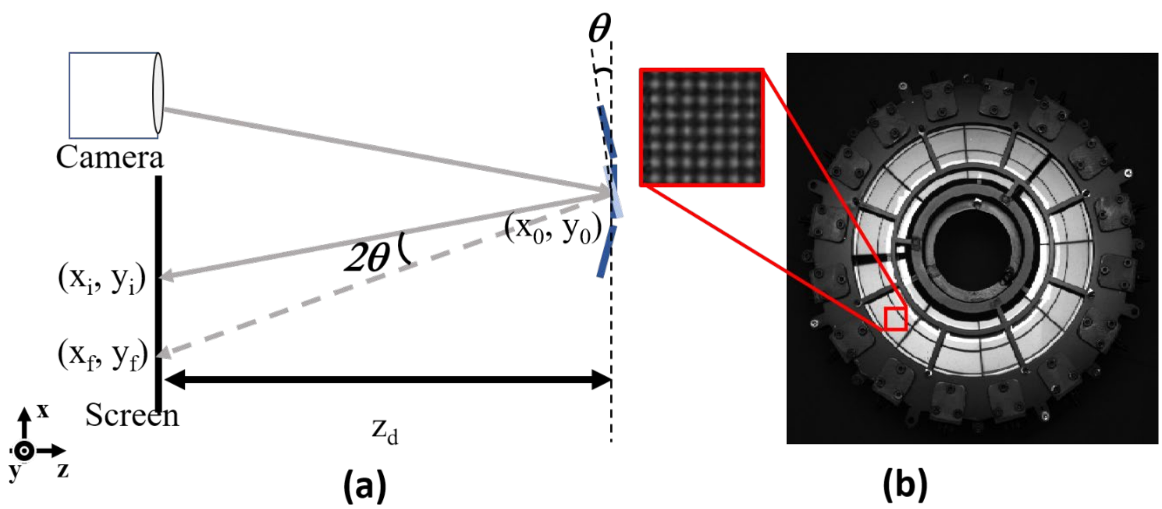

Fig. 3. Schematic diagram of metrology setup[7, 8] and example photo of metrology images. (a) The mirror angle change (θ) induces the twice angle deviation (2θ) on ray and this value can be calculated from the shifted sinusoidal pattern on camera images readily. (b) Raw image of UUT and measured 2D sinusoidal pattern. The camera sees the 2D sinusoidal pattern (inset images) through the opened area once the test iteration is started.

The sheared pattern is obtained by subtracting the reference (initial) image from the refreshed image. Because it subtracts the same sinusoidal pattern with little phase shifting, the FFT results of sheared data show smaller amplitude at the target (initial) frequency. The amplitude variation is translated to tilt angle using the equation below:

Initial pattern frequency bin: $$FT\big(f(x)\big) = F(f) \tag{1}$$

Shifted pattern frequency bin: $$FT\big(f\ (x+\Delta)\big) = e^{-i2\pi f\Delta}F(f) \tag{2}$$

Sheared pattern frequency bin: $$FT[f(x+\Delta) - f(x)] = FT\big(f(x+\Delta)\big) - FT\big(f(x)\big) = (e^{-i2\pi f\Delta} - 1)\ F(f) \tag{3}$$

The shifted phase Δ: $$\Delta = \frac{1}{2\pi f}\left[1 - \frac{1}{2}\left(\frac{\left[FT\big(f(x+\Delta)\big) - FT\big(f(x)\big)\right]^2}{F(f)^2}\right)\right] \tag{4}$$

The phase Δ dimension in Eq. (4) correspond to the x-axis (in Fig. 3 (left)), and it translates to the position of x_f, by the following Eq. (5). The x_i is the initial (i.e., reference) position where the camera looks at the screen through the UUT.

$$x_f = x_i + \text{Pixel pitch in physical units} \times \text{Number of pixels for one period} \times \text{shifted phase } (\Delta) \tag{5}$$

The tilt angle θ then can be calculated by

$$\theta = \frac{1}{2}\left(\left(\frac{(x_i - x_0)}{z_d}\right) - \left(\frac{(x_f - x_0)}{z_d}\right)\right), \tag{6}$$

where z_d is the distance between the UUT and the screen and x_0 is the center of UUT on the x-axis.

3 SMART ASSEMBLY SYSTEM OVERVIEW

The smart assembly system consists of a metrology system and a UV curing lamp (Fig. 4(a)). This all-in-one system controls the monitoring and adjustment of the orientation of the segmented optic. UV curing, epoxy adhesion, and optical welding are existing techniques used to fuse optics. We adopted UV curing which is technically matured with no complicated instruments and possess an easy to restore adhesion status. Some of the existing methods for fusion take anywhere between a few minutes to 1 day before completion and may need enough space for a vacuum chamber or optical system for a laser beam relay. Our metrology technique can measure regardless of time, space, and number of segments as long as the camera field of view covers the entire UUT.

The overall workflow is; 1) align the optical segments under a white light interferometer using a kinematic mount, 2) apply UV resin at the contact area, and 3) cure the resin and monitor. In the case where the metrology system detects the segment position drift larger than the designed tolerance, the lamp is turned off and the system quits the UV curing process. After that, it executes an alignment process again. Alignment processes might be automatic (e.g., actively controlled actuators) or manual. As shown in Fig. 4(b), we currently use a manually adjustable screw for all possible motions, and we utilize the metrology system to examine the alignment quality (whether it is the same as the initial state). Moreover, all screws could be replaced by a motorized actuator for autonomous aligning and curing processes.

In a practical situation, the intense UV light saturates the camera sensor. Therefore, the measurement and UV curing occur every 10 sec sequentially. The microcontroller (Arduino) is adopted to control the UV lamp and the controlling software is written on MATLAB.

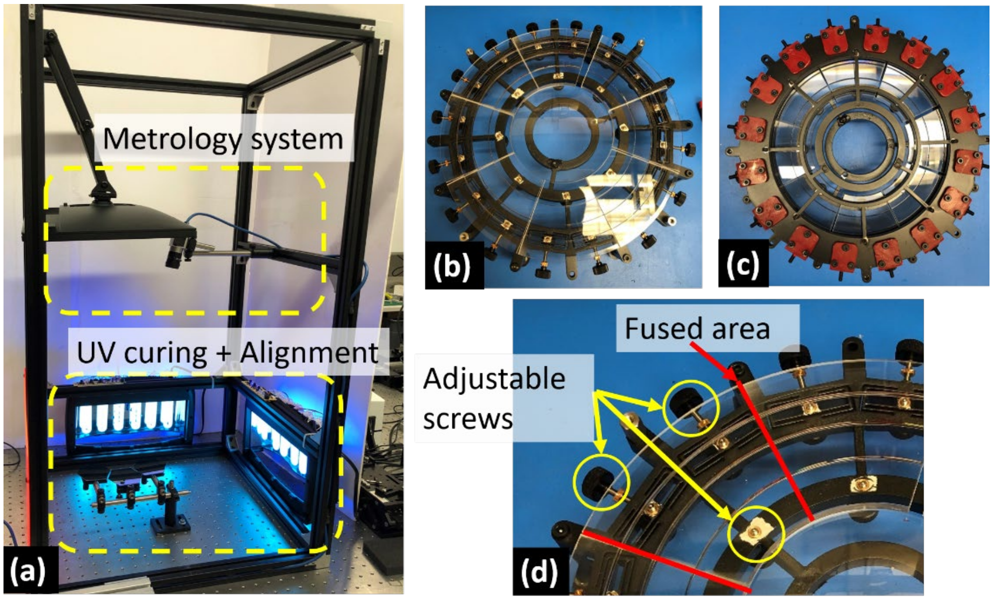

Fig. 4. All-in-one smart assembly system and KEYS. (a) The assembly system consists of two apparatus. Surrounding the UUT stage, the UV curing lamp is placed. On top of the UV curing station, the metrology system is installed. All systems are controlled by a single laptop. (b)-(d) KEYS structure for 25 cm prototyping MODE lens mounting. (b) On the bottom plate of KEYS, the 8 segments MODE lens is installed with three points contact on the adjustable screws. (c) The top plate gives free-loading spring force against three points support. To reduce reflection noise from KEYS, black paint is applied. (d) The tip/tilt, piston and radial translation is the essential motion to alignment. Once the co-phasing is done, the UV resin is applied at the fused area.

4 METROLOGY TEST

The prototype MODE lens is fabricated by diamond turning with PMMA to check the feasibility of the proposed metrology and assembly strategy. The number of segments and radial Fresnel zone sizes are the same as the original glass model but have different surface figures in order to achieve a functional optic performance with the PMMA refractive index. The 8 segments at the outer ring are installed in the KEYS system (Fig 5 (a)), and the metrology system observes the UUT through the KEYS' open area (Fig. 5 (b)). Due to the obscuration by KEYS structure and Fresnel zone boundary on the UUT, the measurable area is divided into many pieces. Each optic segment is presented with a bold yellow line in Fig. 5 (a).

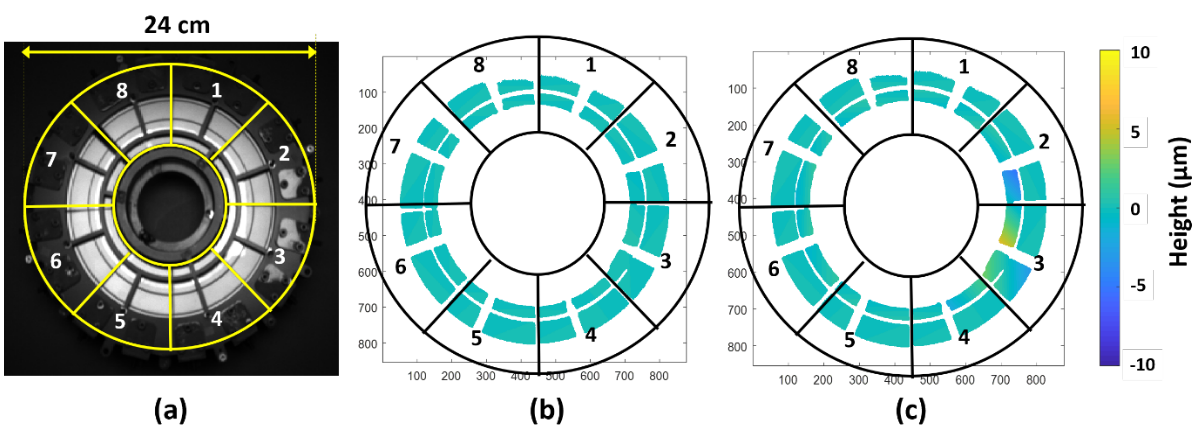

Fig. 5. The real data from the metrology system (a) Live view from the camera. (b) All segments are well-aligned against initial co-phasing status. The black line represents the actual size of the single segment. Due to the obscuration by KEYS, it measures the opened area, which is sufficient to evaluate the misalignment. (c) Segment # 3 drifted from the reference position and the measured tilting angle is 0.006 °. (Note: The X and Y axis of (b) and (c) is in pixel unit.)

Once the system records the reference data, the monitoring iteration is started. Without perturbation of position, all segments remain in their initial state. The #3 segment is tilted by 0.006 ° and the monitoring data shows the tilted value as shown in Fig. 5(c). Because #2 and #4 segments are in contact with #3 at the inside border, they also show the orientation changes. The required resolution of the MODE segment metrology system is ± 0.03 ° in tip/tilt, which can be easily detected by this system demonstrating high sensitivity.

5 SIMULTANEOUS FUSION AND METROLOGY DEMONSTRATION

We used two glass dummy samples for the validation checks and demonstration. Two pieces of glass segments are co-phasing under WLI. The fringe direction and density are used to align two segments. The UV resin is applied at the contact surface before the UV curing where the metrology system will monitor. Once the UV curing is completed, the merged sample is measured to determine if it is in the same initial co-phased state.

Commercial slide glass was used to create segmented samples and glued on the kinematic mount (in Fig. 6 (a)). Because both mounters deviated a lot from the co-phased orientation, we did an initial visual alignment. The rough alignment results are not measurable with WLI. We surveyed height and adjusted to see interferograms on both surfaces at the same time. Afterwards, we precisely adjusted the tip-tilt angle to have a continuous interferogram as shown in Fig. 6 (b). The 3D shape of this status is measured as Fig. 6 (c). The step height is 470 nm and the angle difference of both segments is less than 0.01 °. The tolerances of the optical design are ± 0.03 ° in tip/tilt and 25 μm in the piston. The co-phasing values measured from WLI are safely within the tolerance range.

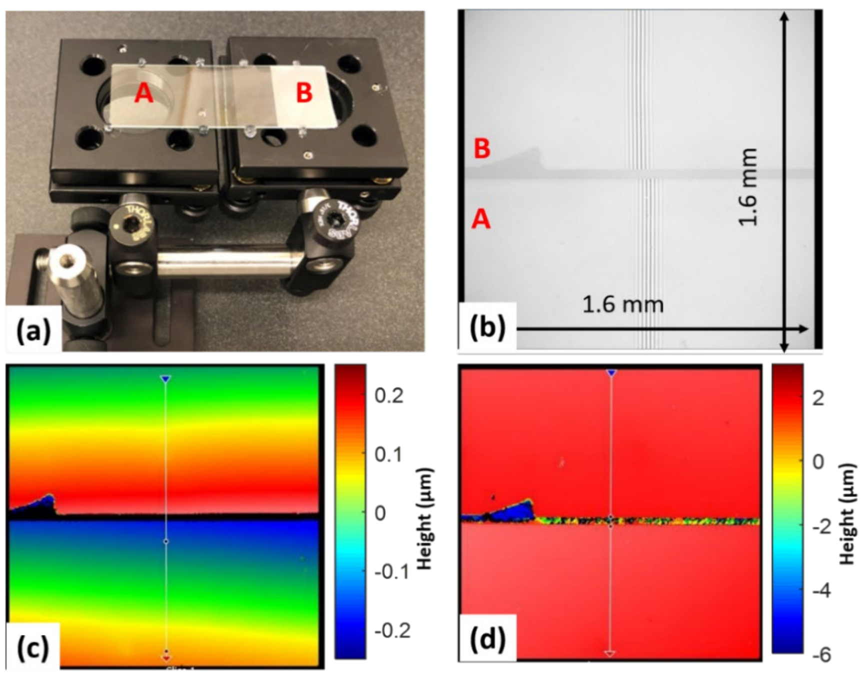

Fig. 6. Glass sample assembly test. (a) Two pieces of glasses are installed on the kinematic mount, respectively. The degrees of freedom of kinematic mount is equal to the KEYS system except for translation. (three points contact, tip-tilt, and piston control). (b) Co-phasing interferogram from the white light interferometer. The fringe density and location are used for co-phasing. (c) 3D information of the co-phased segments. The height difference at the boundary is 470 nm. And relative angle along vertical and horizontal are less than 0.01 °. (d) 3D information after the curing process. The gap is filled with resin and slightly lower than the glass level.

UV resin (NOA 87, Norland Products, Inc.) was applied at the gap (60 μm). Then the sample was installed at the UV curing stage for 1 hour while the orientation was continuously monitored. After the resin was fully cured, the residual resin on top of the glass was removed by alcohol. The co-phasing status was measured under WLI, as shown in Fig. 6 (d). The resin filled the gap and the height and tilt angle difference is shown in Fig. 7. Because the two tests measure a slightly different area, the surface shapes are different. However, the angle and step height remained as same. The step height increased by 40 nm, and the relative angle ($|\theta_1 - \theta_2|$) is 0.002 °. Please note that the units in the plot on the x and y-axis are millimeter and nanometer, respectively.

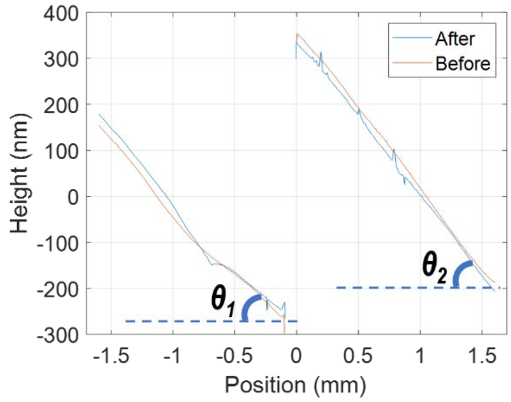

Fig. 7. Lateral profile across the fused area (i.e., around 0 mm position in X-axis) of the before (red profile) and after (blue profile) the UV curing process. The piston and tilt are removed from both data.

6 CONCLUSION

The segmented optics assembly process requires precise metrology, alignment, and assembly capabilities. The presented in-process metrology enables real-time information that is necessary to guide the precision assembly processes by obtaining these three essential capabilities. Because this system has a wide dynamic range, a multi-object measurable algorithm, and high accuracy, the entire assembly process can be implemented under this setup without carrying the UUT for external optical testing. The metrology system is tested with a prototype MODE sample and actual UV curing processes are verified with glass samples. The results show that the proposed method cured the segmented sample with ~0.002 ° angle and ~40 nm piston variation, which is well within the tolerance range of the MODE lens design.

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