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Autonomous closed-loop control for multi-segmented optic aligning and assembly

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ABSTRACT

To meet the scientific requirements demanded for futuristic space exploration, the Nautilus space mission has adopted the newly developed multi-order diffractive optical elements (MODE) design. Primary optics with large aperture diameters, like those used commonly in observatories, are frequently the design most employed and demanded by astronomers. However, this is limited by the difficult challenges that comes with fabrication, alignment, and launch of said optics. The proposed primary optics fabrication breaks through these challenges by using molded segments as its primary optics. With the main advantage of requiring a relatively simplified assembly process and having a compressed volume, the compact form factor will allow for multiple telescope units to be sent together in a single launch. Additionally, the molding and segmented manufacturing creates a fine structure on the diffractive lens surface that is not easy to obtain via traditional surface removal fabrication processes for an identical optical surface piece. The feasibility of this assembly in respect to its accuracy and labor are the key factors of this approach. Therefore, we developed an in-Progress Metrology Control (iPMC) technique that was combined with a motorized mounting system to give us full autonomous closed-loop control during the UV curing of multiple segments. The iPMC monitors and guides the aligning of the adhesion process of the multi-segment MODE, while the metrology system measures the position of the multi-segments so that an individual actuator can automatically adjust the segment's orientation during the UV curing process. This is happening simultaneously as the influence matrix of each actuator receives feedback from the metrology system. The validity of the iPMC is then checked using the mock-up MODE lens assembly.

Keywords: Metrology, in-process metrology, multi-segmented optics, automatic alignment, Close-loop alignment

1. INTRODUCTION

In order to realize the pioneering space mission, advanced techniques such as ultra-lightweight optics are frequently demanded. Therefore we proposed an array of multiple telescopes using an ultra-lightweight primary optics for the Nautilus space mission.[1,2] Fig.1 shows the rendered concept image. The benefits from this experimental and low-cost design would include the maximization of surveying capacity via this multi-unit strategy. The compact launch units are fitted with thin and light primary optics made of the multi-order diffractive engineered (MODE) lens design.[3] Overall, the highest priority in our consideration of this approach are the trade-offs of a simple and robust solution over one that is potentially more complex, costly, and risky.

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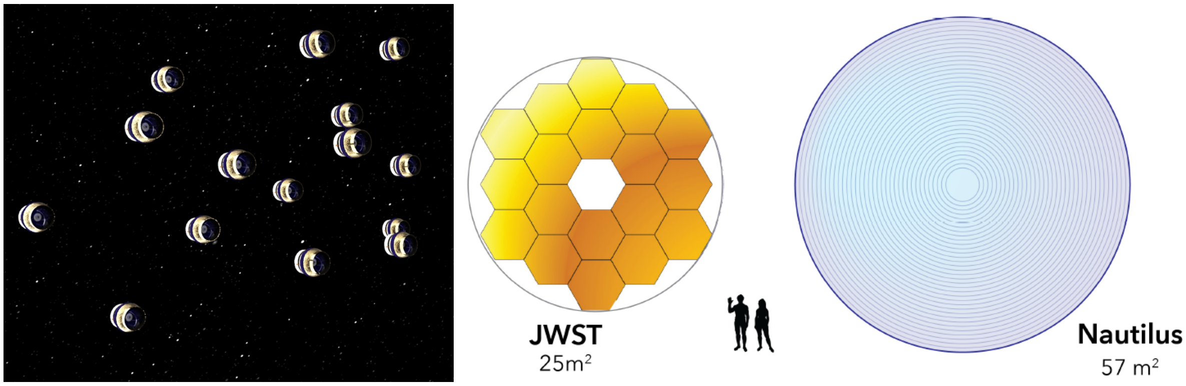

Figure 1. Figures of the Nautilus observatory rendering image and size comparison. (left) The inflatable formfactor allows for multiple telescope unit to deploy in a single launch. (right) Even the single unit area provides a larger collection area than current largest space telescope.

In consideration of these priorities, compression molding for optical manufacturing is a promising technique that can be used to produce the fine features of diffractive lens surfaces. Generally the size of a molded optic is limited by its facility capacity. Having segmented optics enable us to overcome this challenge via the increasing of segment pieces; allowing for larger sizes regardless of facility capacity. Moreover, having identical segmented molded lens pieces will lead to an easy duplication process that can be factored into the manufacturing and assembly/test process.

During segment assembly, optical alignment accuracy is essential for the performance of the telescope. In the previous work, we proposed an in-progress metrology technique that could guide and monitor the aligning of the UV curing of multiple MODE pieces.[4] The advanced deflectometry techniques were applied to extend the measurable number of objects while keeping a few Hz measuring bandwidth.[5,6] At that time, this process was classified as an open loop control. That meant the system would then quit the curing process and the user would have to adjust the kinematically-engaged yoke system(KEYS),[7] shown in Fig. 2 (*right*). Having an open loop control is effective for a small number and size of MODE pieces. However, when the size of the MODE lens extend to the meter class, the one-by-one alignment of mulitple segments would not be practical nor desired.

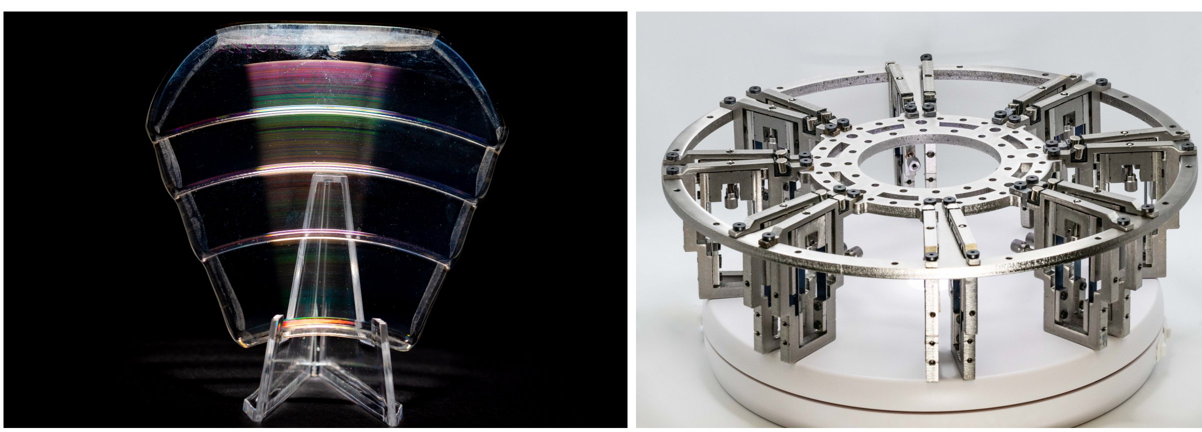

Figure 2. The prototype of the primary optics of Nautilus. (*left*) One of the MODE segments was created via the molding process. The fine structure for diffraction on the optical surface is shown up under a strong strobe light. All eight segments will be manufactured via duplicated molding routine. (*right*) The latest version of KEYS is currently under assembly. It is upgraded from the last version[7] to have the see-through of the assembled MODE so that the point spread function can be measured directly. (Photo credit to Daniel Apai)

In this work, the motor-controlled Kinematically-Engaged Yoke System(KEYS) is proposed to introduce an automatic alignment feature. The alignment fidelity of every segment is monitored simultaneously and the motorized KEYS realigns them if deviation is found. At the preparation stage, the actuators' influence matrix is measured for effective control and then the results from the inverse matrix calculations are fed to the actuators to compensate for misalignment. That autonomous close-loop aligning process is guided by a metrology system which is sequentially operated on by a single desktop computer.

2. MATHEMATICAL MODEL AND CONTROL ALGORITHM

This section describes the mathematical model and control algorithm of the motorized KEYS. The basic concept of the control is through the linear response of the segments' orientation with the motion of the actuator. The allowable motions for the current three points of contact is pistons, tip and tilt.[7] This concept has been widely adopted for deformable mirror control algorithms.[8,9] By taking assumptions of simple linear motion, we are given the equation 1:

$$W = IV \tag{1}$$

where W is the misalignment status of the MODE measured by metrology system, I is the influence matrix, and V is a vector of step numbers for each motors in the KEYS setup. The misalignment status matrix W is determined by the number of segments. With a single segment, the equation 1 is expressed as:

$$\begin{bmatrix} Piston_{s1} \\ Tip_{s1} \\ Tilt_{s1} \end{bmatrix} = \begin{bmatrix} I_{11} & I_{12} & I_{13} \\ I_{21} & I_{22} & I_{23} \\ I_{31} & I_{32} & I_{33} \end{bmatrix} \begin{bmatrix} M_1 \\ M_2 \\ M_3 \end{bmatrix} \tag{2}$$

where the $_{si}$ is the segment #, I_{ij} is the influence matrix component, and M_i is the applied step number for each step motor. At the preliminary stage of the alignment, Matrix I is measured first by driving the motor one by one. Then during alignment, the least square solution of $I \backslash W$ produces the desired motor drive input. This matrix could be easily extended to present the multi-segment MODE as shown in Eq.3.

$$\begin{bmatrix} \begin{pmatrix} Piston_{s1} \\ Tip_{s1} \\ Tilt_{s1} \end{pmatrix} \\ \begin{pmatrix} Piston_{s2} \\ Tip_{s2} \\ Tilt_{s3} \end{pmatrix} \\ \vdots \end{bmatrix} = \begin{bmatrix} \begin{pmatrix} Segment1 \\ InfluenceMatrix \end{pmatrix} & (crosstalk_{2to1}) & \dots \\ (crosstalk_{1to2}) & \begin{pmatrix} Segment2 \\ InfluenceMatrix \end{pmatrix} & \dots \\ \dots & \dots & \ddots \end{bmatrix} \begin{bmatrix} \begin{pmatrix} M_1 \\ M_2 \\ M_3 \end{pmatrix} \\ \begin{pmatrix} M_4 \\ M_5 \\ M_6 \end{pmatrix} \\ \vdots \end{bmatrix} \tag{3}$$

In this extended form, the crosstalk between the segment can also be taken into account because of the practical nature of the operation. In this case, the one group of step motors for one segment (e.g., (M_1, M_2, M_3), disrupt neighboring pieces (e.g., $Piston_{s2}$, Tip_{s2}, $Tilt_{s2}$), the $crosstalk_{1to2}$ will count this impact appropriately. Since we are envisioning a $300\mu m$ gap between the segments and its adjustment during the middle of the soft curing phase, the crosstalking motion during the autonomous alignment should be taken into consideration.

3. METROLOGY SYSTEM CONFIGURATIONS

The benefit of the segmentation of primary optics is that it can successfully emulate the same capabilities of larger aperture optics without being burdened by the drawbacks inherent in its molding system. But this comes with the trade-off of assembly difficulties. However, as a result of the primary lens type, the optical alignment level requires a looser level of tolerance than mirror-type primary optics (e.g., James-Webb space telescope).

To address this, we have developed an advanced deflectometer system that could measure the orientation of the multiple optical surfaces simultaneously.[5,6] Regardless of the number of segments, this system's multitasking capabilities provides the collective misalignment information of segmented optics with an accuracy of 2.7 μrad (1.54 $e^{-4}deg$) in tip and tilt. As shown in the Table 1, the required accuracy of the MODE assembly can be easily attainable.

	Piston (μm)	Decenter (μm)	Tip/Tilt (°)
Outer rim segments	25	3	0.03
Center circular segment	30	20	0.05

Table 1. Tolerance ranges of MODE segments assembly. They have a relatively looser tolerance than general segmented optics because of the lens type optics.

It is worth admitting that the metrology system might not be sensitive enough for the piston and lateral translation. This is because of the slop testing inherent in deflectometry. The top priority of the alignment and assembly is making a continued surface over the glued sample. Then the next priority is having them all in a parallel optical axis. Considering the relatively looser tolerance of the piston and tighter tolerance in angle of the tip/tilt, the segments should be handled with attentive care. In this context, slop-sensitive metrology will accomplish an appropriate role in guiding the gluing process. The clear zonal boundary of multi-order diffraction can be the criteria used for lateral misalignment via machine visual inspection. When random misalignment occurs on the optical surface, the decomposition of motion has an angle component as well. This can easily be detected by our metrology system. Moreover, the three points of contacts underneath the MODE segments wouldn't induce the lateral error motion while restoring the angle.

Throughout the initial alignment of the segments, the surface continuity is first measured by the white light interferometer (WLI). Then KEYS will hold it over the UV curing process. Transporting the segments between the two is accounted for since the segments can readily keep their positions under the magnet force from the WLI to the UV curing platform. After that, the metrology system takes an initial state orientation and does a comparison test to check the drift of the segments during the curing process.

4. EXPERIMENT SETUP

The curing system, metrology and motorized KEYS control are executed on a single machine. On top of the KEYS and UV lamp platform, the metrology system look down the KEYS and mounted MODE lens through a large enough field lens to cover all segments (Fig. 3 ($left$).) The metrology system is composed of the Basler camera (acA2040-120um) and an off-the-shelf monitor (LG, 24-inch, 24BK550Y-I). As the sinusoidal pattern is displayed on the monitor, the acquisition camera takes the reflected sinusoidal pattern against the unit under test (UUT). In this setup, the camera will see a fraction of the sinusoidal due to the zonal divide surface. However, it still gives a sufficient enough amount of information to evaluate the misalignment. The Matlab code then sequentially implements these three steps, testing - adjustment - UV curing, automatically until the resin is fully cured. The flow chart of the control algorithm is shown in Fig. 3 ($right$).

The Arduino microcontroller is adopted for the UV light and motorized KEYS control. The prototype MODE design consists of 8 segments for the rim + one center circular lens. The PMMA mockup of how it optically functions has been fabricated for testing of the alignment and assembly, but wasn't used in this stage due to difficulties rolling back the cured resin. Instead, a 3D printed mockup is mounted on the motorized KEYS and the unique structure of the MODE lens that interfaces with the three points of contract is tested over the process. In this verification process, the motorized stage for two segments is built. However, extending to 6 segments support is straightforward because of its symmetrical structure (Fig. 4).

We could reduce the number of iterations by using a strong UV light, but that carries the risk of hard curing in a wrong alignment before it is recoverable. Moreover, we are envisioning the potentially long assembly and glue process when the meter class MODE is built. In the middle of the soft curing step, the segments could be re-adjusted ahead of the hard curing phase and this is beneficial when we are working on serious optics.

The 3D printed MODE lens pieces have a low reflectance and the current metrology system could not measure the reflective fringes from it. To account for that, the slide glasses were attached to the top surface so that the

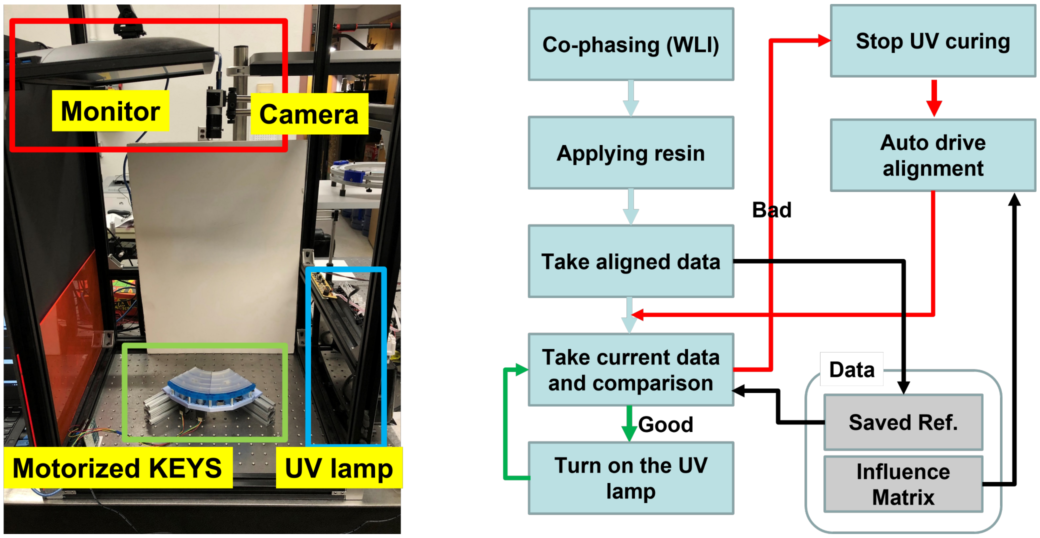

Figure 3. The photos of the experimental setup and schematic flowchart of the control algorithm. (*left*) The metrology system (red box) monitors the entire MODE assembly (green box) from a top view. The position of the monitor and camera can be relocated to see the reflected off fringes from the UUT to the acquisition camera. The fluorescent UV lamp array are placed on the right side (blue box). (*right*) The control code consisted of multiple modular subroutines for metrology and control. The green loop represents the UV curing loop when the misalignment passes the criteria. When misalignment is over the criteria, the process cycles through the red line loop until the segments are back to co-phasing mode.

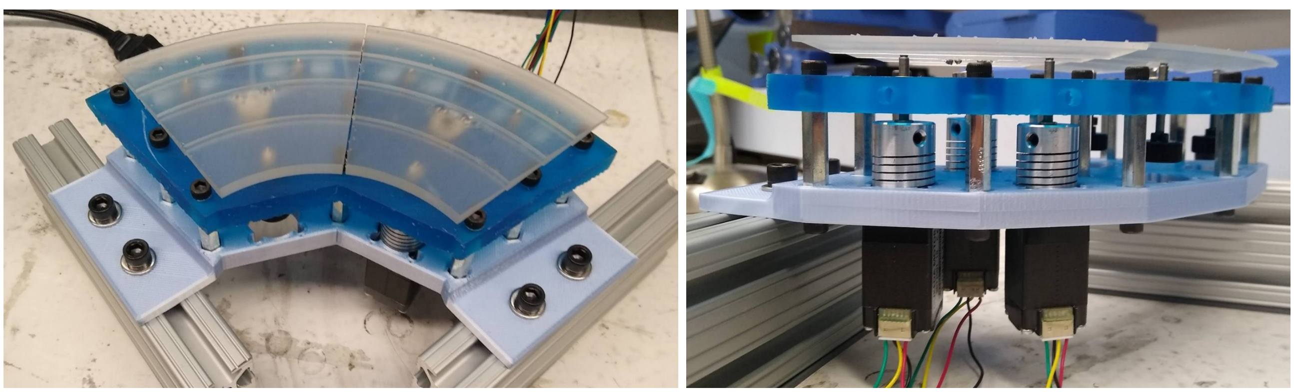

Figure 4. We used a two segment mounting setup for the validity checking stage. (*left*) Two 3D printing mockup segments are mounted on top of the motorized KEYS for fast track testing. The relative alignment between both segments are then measured and evaluated. One of segment is mounted on the manual adjustment knobs and another is mounted on the motorized side. Both manual- and motorized-adjustment screws are placed to support the exact same structure datum on the underneath of MODE. The zonal step of the MODE gives the stable positioning of MODE with regard to three contact points. (*right*) The NEMA 8 stepper motor, and minimum step of the motor gives 1.25 μm stroke motion. The combination of the the three motor's motion creates the piston movement and the tip and tilt. However, satisfied amount of motion should be applied to give orthogonal motion.

reflection fringe signal could strongly be shown as seen in Fig. 5. Once the segment has been aligned by using the adjustment knob, the metrology system measures the initial state and it is saved for reference. During the curing process, the metrology system detects deviation from the reference and calculates the required step motion via the equations show in 3 during the close looped operation.

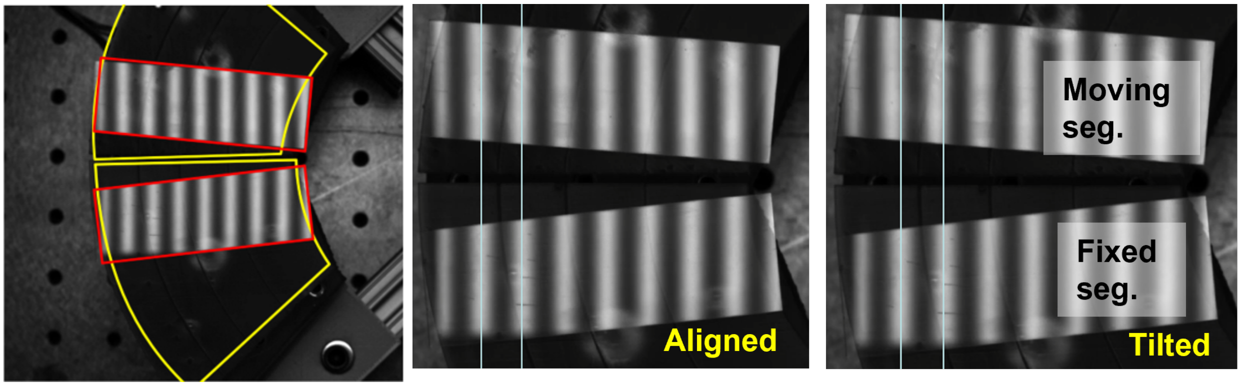

Figure 5. The acquired images of the motorized KEYS and fringes from the metrology system. ($left$) The cropped images of metrology system. The yellow boundary indicated the 3D printed mockup MODE. As noted, it barely reflects the fringe signal. The attached slide glass provides a bright enough fringe. The above segment is mounted on a motorized support and the below one is mounted on a manual adjustment support. (mid) The system saved the data from this raw image as a reference and all following iteration loops shows the fringes in a perfect alignment. ($right$) The given actuation motion is applied to above segment. It shows the clearly shifted sinusoidal pattern.

4.1 Realigning Performance

The accuracy of the step motor control is now evaluated. In the setup, the M3 fine screw is engaged to the step motor driver directly. The rotation of the step motor induces the same angle revolution to the M3 screw. When a large motion of segment is required (e.g., initial alignment right after engaging MODE onto KEYS), the set screw on the shaft coupling and step motor is released and the subsequent hand winding produces the desired large motion. After that, the segment deviation is less than the automatic adjustable target range. The set screws are locked out and adjustment control becomes necessary to be administered via software. The flexible structure of the shaft coupling gives a reasonable screw stroke, but nevertheless it should be carefully investigated.

One revolution of M3 screw gives 250 um of travel, and 200 steps generate 1 rev of the step motor. With the above specs, the smallest step motion is 1.25 $\mu m/step$. The actual motion fidelity of the actuator is measured using a dial gauge as shown in Fig. 6. The stylus is placed on the MODE lens. Specifically, on top of the point that contacts with the position of one of the actuators. With 100 steps in the max range of the automatic control environment, the top surface of the MODE lens moved 101.6 μm. This differs from the specifications laid out by 23.4 μm. The error is caused by the stress of the 3D printed body structure and shaft couplings. However, the metrology system resolution is 8.6 μm and the extra iterations of small steps could recover the desired motion of the segments without needing to analyze structure stress, backlash, and linearity of the control sequence.

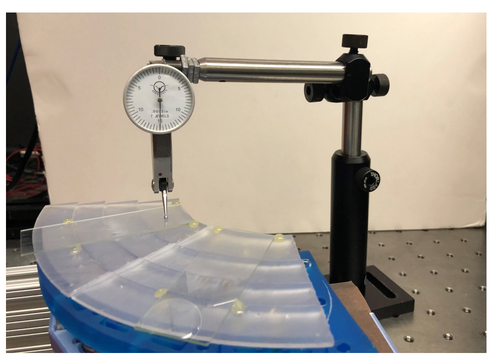

Figure 6. The dial gauge measured the actual motion at the point contact position of one of the actuators. The actuator ball tip contacts with the underneath zonal edge structure, and the slide glass is attached to create the high reflection images for the metrology system. The gauge stylus is engaged on the slide glass surface.

The motion control module consist of two steps in order to address the discrepancy of the expected motion from eq. 3 and the actual motion. The first step uses the feed from the large step influence matrix to place segments within $\sim 20\mu m$ of accuracy. Then, the small step influence matrix is used to suppress misalignment via multi iteration. In practical operation, these two step controls will be proceed in parallel for multi-segment control. They could be aligned simultaneously while in consideration of cross talking between the motion of neighboring segments.

5. CONCLUSION

The automatic alignment and curing system for the Nautilus mission was built. Using multiple segments as the primary optic for Nautilus required a unique strategy in order to meet the uncommon aligning and assembly required. In this paper, the motorized KEYS shows the validity of the autonomous process for multiple segment alignment under a single unit metrology/alignment/curing system. The simplified influence matrix allows concise feed for the motorized KEYS with large and small deflections. Our system gave an orthogonal accurate motion for segment control. As a result, we fully expect that this approach could be easily extended to a larger MODE designed aperture with more segments.

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