Programmatic Large Precision Optics Manufacturing

Dae Wook Kim[1,2*], Maham Aftab[1], Isaac Trumper[1], Logan Graves[1], Henry Quach[1], Hyukmo Kang[1], Xiangyu Guo[1,3] and Heejoo Choi[1]

[1]James C. Wyant College of Optical Sciences, Univ. of Arizona, Tucson, AZ 85721, USA

[2] Department of Astronomy and Steward Observatory, Univ. of Arizona, Tucson, AZ 85719, USA

[3] J. Mike Walker '66 Department of Mechanical Engineering, Texas A&M University, TX 77843, USA

*letter2dwk@hotmail.com

Abstract:

Freeform optical surfaces have seen wider spread adoption with the development of manufacturing and testing technologies that enable their use. A suite of astronomical/large optical system design optimization, testing, and fabrication approaches have been developed to support various freeform optics manufacturing projects.

Keywords: Freeform optics manufacturing, Large optical system design, Optical surface postprocessing.

1. Introduction

A suite of precision large optics manufacturing methods has been investigated and developed to support various freeform optics manufacturing projects. Four enabling technologies are summarized with full references [1 – 6].

2. Large Precision Optical System Design and Manufacturing Technologies

2.1 Mathematical Vector Data Processing

We have derived a set of vector polynomials, orthogonal in the rectangular domain, that can fit the gradient and curl of surface or wavefront data, called G [1] and C [2] polynomials respectively. Both sets are obtained from the 2D Chebyshev polynomials of the first kind, a scalar basis set also orthogonal in the rectangular domain. The combined set of G and C polynomials can fit any vector data across rectangular apertures with ease and high accuracy. Generating a very large number of terms is efficient and makes it ideal for high-resolution or freeform surfaces, gives good reconstruction accuracy when the measured surface has blockers or markers on it (such as fiducials or scratches), and allows it to perform complex systematic error analysis and corrections for metrology systems [1, 2].

2.2 Dynamic Configuration Optical System Design

When choosing to use a freeform surface in an optical design, we should be judicious in our application, maximizing their impact. To guide this freeform surface selection process, a parametric fitness function using modal wavefront fitting has been investigated [3]. Further, we have investigated an additional application of freeform surfaces to a dynamic optical configuration [4]. We present a use-case of a K-mirror with a linear field of view and compare the optical performance benefits with respect to other typical surface definitions. These developments in the freeform design space provide more tools for the optical designer when freeform surfaces are needed. As an example, Fig. 1 (left) shows a millimeter-wave instrument design using freeform surfaces in a K-mirror. This design was also used to validate the parametric fitness function used to guide the surface selection process.

2.3 High-Contrast Infrared Deflectometry

Infrared deflectometry is a valuable metrology tool for measuring rough optical surfaces, which do not reflect visible wavelength specularly. While infrared deflectometry has historically relied on heated sources (e.g., tungsten wire) to emit infrared light for testing an optic, this source has limited achievable signal power and appreciable temporal behavioral uncertainty. In order to

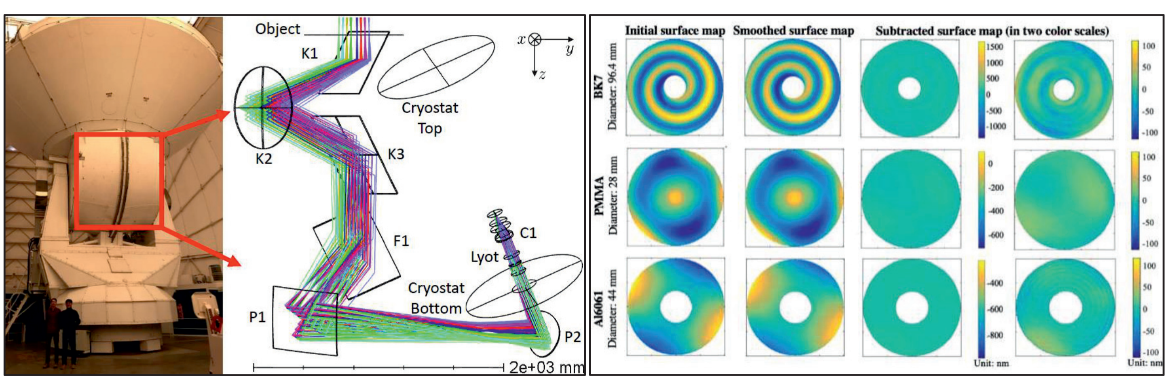

Fig. 1: (left) The millimeter-wave instrument design created for the Tomographic Ionized-carbon Mapping Experiment (TIME) using the 12 m Radio Telescope at Kitt Peak. The surfaces K2, P1, P2, and C1 are freeform while the surfaces K1, K3, and F1 are flat [3]. (right) Measured full-aperture surface maps using Verifire™ interferometer for the initial and smoothed stages, and the corresponding subtracted surface map showing the difference before and after the PROS process. [6].

increase testing accuracy and the range of measurable surfaces, a Long-wave Infrared Time Modulated Integrating cavity Source (LITMIS) design was created [5]. The design utilizes a scalable array of resistive blackbody elements that inputs radiation into a custom integrating cavity with a defined exit slit. Temporal modulation of the input radiation at 1 Hz can be achieved electrically and allows for signal isolation. Based on initial results, the LITMIS features a more ideal emission pattern, roughly 4 times less temporal variation, and nearly 4 times larger signal-to-noise ratio.

2.4 Freeform Optics Post Processing

While various computer controlled optical surfacing methods (e.g., single point diamond turning) can achieve a desired freeform profile, ensuring a superb micro-roughness finish is the key factor for successful freeform optics manufacturing. Aiming at both maintaining the freeform optical surface form and decreasing the high spatial frequency surface errors (i.e., surface roughness) for various optical materials and freeform manufacturing methods, we developed a pseudorandom orbiting stroke (PROS) computer numerical control (CNC) postprocessing technique, which can be applied to varied optics sizes, materials, and pre-polishing methods [6]. The full-aperture tool can avoid sub-aperture effects, and the small stroke pseudorandom tool path guarantees the match of freeform profiles while preventing the directionality of the final surface profiles. Three representative experimental case studies using freeform optics made out of glass (BK7), plastic [Poly(methyl methacrylate) or PMMA], and aluminum (Al6061) for diameters ranging from 30 to 100 mm are presented in Fig. 1 (right) to prove the performance of the proposed postprocessing technique.

3. Concluding Remarks

Programmatic large precision optics manufacturing solutions are the critical components enabling unprecedented imaging performance for astronomical telescopes and instruments of next generations. The comprehensive series of optical engineering methods covering the mathematical foundation for data processing, educated optical design, earlyphase metrology, and freeform optics post processing technique has been successfully developed and demonstrated.

4. Acknowledgment

This research was made possible in part by the II-VI Foundation Block-Gift Program, the Korea Basic Science Institute Foundation, the Technology Research Initiative Fund Optics/Imaging Program, and the Friends of Tucson Optics Endowed Scholarships in Optical Sciences.

5. References

[1] M. Aftab, J. H. Burge, G. A. Smith, L. Graves, C. J. Oh, and D. W. Kim, "Modal Data Processing for High Resolution Deflectometry" Int. J. of Precis. Eng. and Manuf.-Green Tech., 6: 255 (2019).

[2] M. Aftab, L. R. Graves, J. H. Burge, G. A. Smith, C. J. Oh, and D. W. Kim, "Rectangular Domain Curl Polynomial Set for Optical Vector Data Processing and Analysis", submitted to Optical Engineering (April 2019).

[3] I. Trumper, M. Aftab, and D. W. Kim, "Freeform surface selection based on parametric fitness function using modal wavefront fitting," Opt. Express 27 (5) 6815-6831 (2019).

[4] I. Trumper, D. P. Marrone, and D. W. Kim, "Utilizing freeform optics in dynamic optical configuration designs," submitted to J. of Ast. Tele., Inst., and Sys. (2019).

[5] L. Graves, H. Quach, R. J. Koshel, C. J. Oh, and D. W. Kim, "High contrast thermal deflectometry using long-wave infrared time modulated integrating cavity source", submitted to Optics Express (June 2019).

[6] X. Guo, Y. Shu, G. H. Kim, M. Palmer, H. Choi, D. W. Kim, "Pseudorandom orbiting stroke for freeform optics postprocessing," Opt. Eng. 58 (9) 092608 (2019).