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Freeform optics: introduction

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Abstract: This feature issue of Optics Express highlights 28 state-of-the-art articles that capture a snapshot of the recent developments in the field of freeform optics. As an introduction, the editors provide an overview of all published articles, which cover a broad range of topics in freeform optics. The wide variety of applications presented here demonstrates that freeform optics is a growing and vibrant field with many more innovations to come.

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1. Introduction

Freeform optics is an emerging technology that is transformative for imaging and non-imaging optics. Freeform optics has permeated many application areas including optical transformations (e.g., quantum cryptography, art forms), lighting and illumination (e.g., luminance, architecture lighting, automotive), manufacturing (e.g., EUV lithography, laser materials processing, machine vision and inspection), mobile displays (e.g., near-eye, head-worn, handhelds, smart glasses), remote sensing (e.g., down-looking satellite, ubiquitous data collection, astronomical instrumentation, CubeSat), infrared and military instruments (e.g., UAVs and drones, conformal optics, and intelligence surveillance and reconnaissance systems), energy research (e.g., photovoltaics, laser beam transport synchrotron), transportation heads-up displays, lidar), and medical and biosensing technologies (e.g., assistive technologies, endoscopy, microscopy) [1]. The technology requires expertise in bringing together cross-disciplinary design, fabrication, and testing fields.

In the design of freeform optics, there are emerging methodologies for the mathematical description of freeform optics, continuing developments in the generation of starting points for a design, surveys or models that provide the designer with sufficient information to make design decisions, as well as ongoing developments in the final design optimizations.

The fabrication of freeform optics (or optical molds) involves historically deterministic computer numerical control grinding, polishing, and diamond machining. The challenge in these techniques includes building knowledge of how materials behave, especially as manufacturing pushes increasingly higher feeds and speeds. Some exciting developments are the recent advances in additive manufacturing that enable the 3D printing of freeform optics.

Optical metrology techniques remain the “elephant in the room”. The measurement time and complexity of the metrology solution are directly related to the manufactured freeform optics costs. Sophisticated solutions are affordable for high-end (e.g., EUVL industry) or high volume (e.g., cell phone camera lenses) applications. However, a current challenge is for low-volume, moderate-uncertainty metrology, where the costs of a metrology solution conflict with the desired tolerances. Fast non-contact metrology of surface shapes will remain in demand as a critical enabler for convergence to manufacturing chain specifications.

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This feature issue of Optics Express highlights 28 state-of-the art articles that capture a snapshot of the exciting developments in the field of freeform optics, where a total of four papers have been published on the mathematical descriptions of freeform optics, 13 papers on the design of freeform optics and applications, four papers on fabrication methods, and seven papers on the metrology of freeform optics. Here, the editors provide an overview of these published articles. The wide variety of applications presented here demonstrates that freeform optics is a growing and vibrant field with many more innovations to come.

2. Mathematical description of freeform optics

The imaging performance evaluation of symmetry-free optical systems is of great importance during the correction process of optical design. The well-known Nodal aberration theory (NAT) was developed to six-order, and the mathematical formulas grow strongly in length and complexity when describing higher-order aberrations [2]. Tang and Gross introduce a mathematical approach of a quantitative analysis method for surface-decomposed transverse aberration in symmetry-free systems [3]. A mixed ray-tracing technique (MRT) is investigated for an extension to a broader application range to evaluate the surface-related aberrations in the symmetry-free systems in various aspects. The implementations of full-order intrinsic/induced aberrations and the surface-additive Zernike coefficient fitting method are demonstrated.

Tang and Gross also report on various practical applications of the MRT method [4]. An example is presented using a group of representative realistic lithography systems. The results of the calculation are analyzed and represented by surface-resolved plots, together with a summary of performance assessment.

Anthonissen *et al*. report a unified mathematical framework for sixteen fundamental optical systems [5]. The mathematical model for each system is based on Hamilton's characteristic functions and conservation of luminous flux. When using this framework, three systems are described by the standard Monge-Ampère (SMA) equation, and two systems are governed by the generalized Monge-Ampère (GMA) equation. Either of the previous two models cannot describe systems with near-field targets. The authors propose a more general formulation to describe these systems using so-called generating functions that lead to generated Jacobian equations.

Lippman *et al.* report on a new class of freeform optics with freeform gradient-index (F-GRIN) media [6]. F-GRIN leverages arbitrary three-dimensional refractive index distributions to impart unique optical influence. When transversely variant, F-GRIN behaves similarly to freeform surfaces. By introducing a longitudinal refractive index variation, F-GRIN optical behavior deviates from that of freeform surfaces due to the effect of volume propagation.

3. Design of freeform optics – roadmaps and starting points

Bauer and Rolland present a roadmap for an unobscured three-mirror freeform design space utilizing freeform surfaces [7]. This roadmap provides designers of these systems with pre-design information to make informed design decisions such as prioritizing cost-effective designs over compactness. The authors aim for this roadmap to enable designers to narrow down the explorable solution space to solve their problems. Volume tradeoffs with metrics such as freeform departure and slope can be further studied and optimized. The authors envision that this work will inspire other researchers to create roadmaps in freeform design areas that explore a wide range of system parameters including reimaging, number of mirrors, floating stops (for telecentric systems), and look at the scalability to other spectral ranges.

Papa *et al.* report on a four-mirror freeform imager solution space survey [8]. This survey is a grid search over the parameters that remain after reducing the solution space's degrees of freedom using first-, second-, and third-order aberration theory. A final optimization is carried out for higher-order surface shapes through sixth-order. The authors also discuss general trends in the systems' performance versus volume and etendue and their utility in trade studies.

Chen *et al.* propose a deep learning framework to generate starting points for freeform imaging optical design [9]. The deep neural network can then be trained in a supervised manner and can be used to generate good starting points directly. The authors demonstrate this approach by designing a freeform off-axis three-mirror imaging system, a freeform off-axis four-mirror afocal telescope, and a freeform prism for an augmented reality near-eye display.

4. Design of freeform optics – beam shaping

Bykov *et al.* propose a method for designing refractive optical elements with two working surfaces that transform an incident plane wavefront into an output beam with a prescribed irradiance distribution and a non-planar wavefront [10].

Yang *et al.* present an optical design of a beam shaping system that produces variable illumination properties on a fixed target plane [11]. The beam shaping system is composed of a freeform lens and a non-classical zoom system that is not a typical imaging system. The illumination pattern produced by the beam shaping system can be scaled up and down by moving the lens elements included in the zoom system to match the different regions of interest on the fixed target plane without changing the working distance.

Si et al. propose a freeform optics design for laser beam splitting to generate a target spot array [12]. This design generates an intermediate Gaussian sub-beam array to reduce diffraction effects, in particular for cases where the size of each Gaussian sub-beam is sufficiently larger than that of the corresponding sub-area within the input beam. All the Gaussian sub-beams have the same optical field distributions, which thus can produce identical discrete spots on the target plane.

5. Design of freeform optics – applications

Liu *et al.* report on a compact hyperspectral imager design consisting of a freeform reflective triplet imager and a freeform reflective triplet spectrometer used in double-pass configuration [13]. The design operates near F/2 with a 15-degree cross-track and a 30 mm entrance pupil diameter while achieving a small volume of fewer than two liters that fits comfortably within a 3U CubeSat geometry.

Zhang et al. demonstrate a freeform imaging spectrometer design that employs a dimensionality reduction technique as an initial solution followed by a neural network to fit the relationships among the systems' structures, optical power distributions, and imaging qualities [14].

Freeform lenses also enhance optical camera communication (OCC) systems. Liu *et al.* showed that the low signal-to-noise ratio caused by the non-uniform irradiance distribution produced by the LED can be mitigated using a freeform lens that produces a uniform rectangular illumination [15]. The system employing this freeform lens has a packet reception rate that is improved by 35% and a bit error rate that is decreased by 72%.

Wu et al. expand on a design method they priorly proposed using the concept of field focal length to create freeform optical systems with 2D field-dependent parameters, [16]. The authors demonstrate this approach for an off-axis reflective freeform imaging system with high center resolution and low edge resolution within a square 30°×30° field of view (FOV). Only three freeform surfaces are used to attain a good image quality.

Moein and Suleski present a design method to enable extended depth of field (EDoF) imaging for a range of numerical apertures using freeform phase plates [17]. This approach can decrease the number of parts needed to enable EDoF imaging for multiple systems and potentially reduce system costs.

Shadalou *et al.* report on a general design approach that enables dynamic variation of illumination patterns with high uniformity in an LED-based system using arrays of freeform Alvarez lenses [18]. The starting point for the design was defined by applying paraxial geometrical optics concepts followed by an optimization process. The optimization process uses

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an infinitesimal monochromatic Lambertian source, and a small number of rays followed by gradually increasing the number of rays and replacing the source with a real LED model.

Kim *et al.* outlines a methodology for illumination optics tolerancing, where the authors investigate tolerancing deformation of a single freeform surface under a point source illumination [19]. Three surface-deformation characteristics have been identified that allow the designer to build tolerancing intuitions. The simplicity of the method opens a door for a fast and predictable tolerancing approach. The method introduced is meant to encourage tolerancing illumination optics more often and become a steppingstone in developing advanced tolerancing analysis for illumination optics.

6. Fabrication methods

Sorgato *et al.* present the design, tolerancing, and fabrication of a miniature freeform optical light guide for sensing applications. The light guide's shape and size are strongly limited by the geometrical constraints of the available volume ($1.3 \times 2.0 \times 20$ mm3) [20]. The main optical feature of the light guide is a 45° acceptance half-angle at its entrance port, which faces the incoming radiation.

Toulouse et al. present a methodology to design, fabricate and realize 3D-printed freeform lenses as a toolbox with many applications [21]. The authors present concepts, correction methods, and realizations towards freeform multi-aperture wide-angle cameras fabricated by femtosecond direct laser writing (fsDLW). The iterative approach is straightforward and advances the producibility of lenses with shape fidelities up to λ/10 without the need for complex models of time-dependent polymerization processes. The 3D printing process enables the design freedom to create $180° \times 360°$ cameras with a flat form factor in the micrometer range by splitting the FOV into several apertures. The authors demonstrate two realizations of freeform multi-aperture wide-angle cameras.

Aderneuer *et al.* demonstrate that two-photon grayscale lithography is a significant advance in additive manufacturing [22]. Specifically, it is found to decrease fabrication times compared to two-photon polymerization while maintaining excellent form accuracy and surface roughness even for non-spherical microstructures with planar facets and relatively sharp edges and corners.

Majumder *et al.* engineered the point-spread function (PSF) of a low-f-number freeform diffractive microlens array to enable an extended depth of focus (DOF) [23]. Each square microlens of side length 69 µm and focal length 40 µm is achromatic over the visible band (450 to 750 nm) and exhibits an extended DOF of +/-2 µm with a geometric f/# of 0.58 in a polymer material. The microlens array was nanoimprinted directly onto a 40 µm-thick polymer film and could be integrated into high-resolution prints or displays for 3D integral imaging. Applications are found in 3D displays, light-field cameras, wavefront sensors, and many other applications.

7. Metrology of freeform optics

Huerta-Carranza *et al.* propose measuring the shape of freeform surfaces by applying the null-screen method in a reflective deflectometry configuration [24]. The reconstruction involves an iterative algorithm to retrieve the surface under test and calculate the frontal freeform's spherical and cylindrical dioptric powers.

DelOlmo-Márquez *et al.* demonstrate an exact ray-tracing approach applicable to plano-freeform Zernike surfaces that provide both sagittal and tangential caustic surfaces [25]. The authors provide exact formulas to represent the wavefronts propagated at arbitrary distances from the Zernike surface. When placing the detection plane inside the caustic surfaces, these expressions can be used to evaluate the shape of Zernike surfaces using the null screen method.

Ramirez-Andrade *et al.* report a new approach to optical measurements entitled "Vision ray metrology" [26]. The principle is based on the simple deflection of rays. This optical configuration significantly reduces the complexity of the reconstruction algorithms. Unlike Deflectometry, the

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proposed vision ray metrology system does not require mathematical optimization algorithms for calibration and reconstruction – the vision rays are obtained using a simple 3D fitting of a line. Applications of this work are the metrology and alignment of freeform optics.

Shahinian *et al.* report an analysis of the retrace error in the interferometric measurement of freeform optics using stitching techniques with a commercial coherence scanning interferometer (CSI) [27]. It is shown that measuring segments of freeform optics under non-null conditions requires an approach that quantifies the induced aberrations based on the local slopes of the surface. The proposed correction method uses those experimental measurements to determine the required correction based on the local slope and position in the aperture.

Berlakovich *et al.* present an algorithm for the precise registration of multiple wavefront segments containing large misalignment and phase differences [28]. The authors show that for misalignments up to 100 µm and 3 mrad, it is possible to obtain a registration error near 10 nm if 40% of the sensor aperture area of the measurements overlap.

Alignments are critical in optical metrology systems, especially when working with interferometers. Gronle *et al.* show that simply removing tilt and power terms of the measured surface may introduce significant errors in the surface shape in the case of aspheres and freeforms [29]. The authors recommend an exact analysis if errors resulting from misalignment are correctly considered.

Swain *et al.* report an Optical Differentiation Wavefront Sensor based on a telephoto lens system and binary pixelated filters [30]. An experimental investigation shows that the system has a high tolerance to components alignment errors and provides a five-fold reduction in the system length compared to other Optical Differentiation Wavefront Sensors.

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