Enabling Scalable Production of Freeform Mirrors through Optical Replication

Spectrum Scientific, Inc.

Introduction: The Evolving Role of Freeform Optics

Since the 1970s, freeform optics have emerged as a powerful tool in the design of advanced optical systems. Characterized by their non-rotationally symmetric surface geometries, freeform optics enable more flexible light path control than conventional spherical or aspheric surfaces.

Historically, the use of these optics was confined to niche applications in defense, aerospace, and high-end scientific research, largely due to the complexity and high cost of manufacturing.

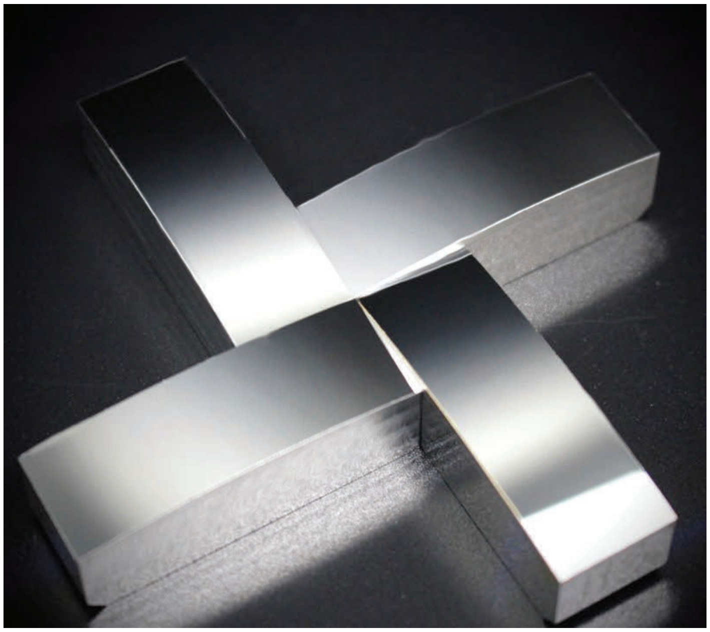
The enabling technologies were developed in the 1980's and 90's when Deterministic Manufacturing Processes came of age.

- **Consistency of CNC machining**
- **Single point diamond turning**
- **Deterministic Micro-grinding**
- **Magnetorheological Finishing**

In recent years, however, there has been increasing interest in leveraging freeform optics for broader applications, particularly in imaging systems for life sciences, analytical instrumentation, industrial inspection, and medical diagnostics.

The challenge has remained: how can manufacturers scale production of these precision components to meet commercial demand - without compromising on quality or incurring unsustainable costs?

This white paper explores the limitations of traditional freeform manufacturing methods and introduces Spectrum Scientific, Inc.'s (SSI) proprietary optical replication process - a solution that bridges the gap between design innovation and scalable, cost-effective production of high-specification freeform mirrors



Optically Replicated Freeform Mirrors

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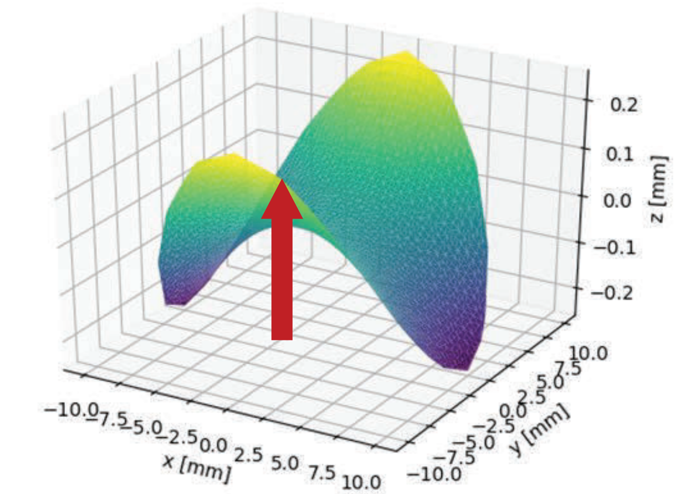
What is a Freeform Optic?

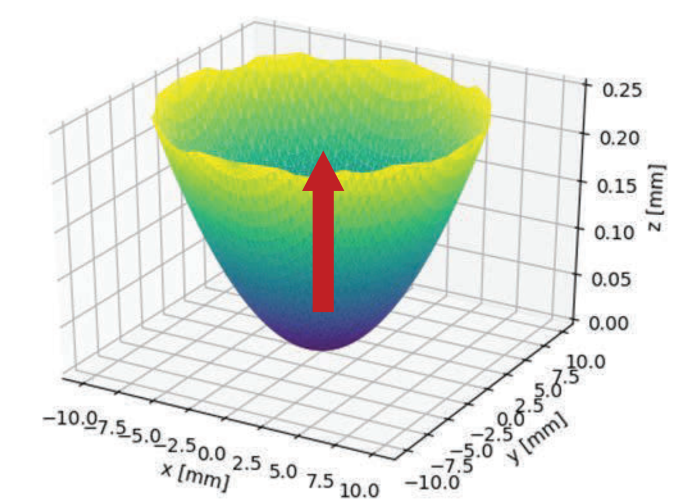
According to the ISO 17450 standard, '**Any surface that has no translational or rotational symmetry relative to the normal of the average plane'** is a freeform optic.

Or put simply, a freeform optic is an optical surface that lacks rotational symmetry about any axis. Unlike traditional spherical or aspheric optics, which are symmetrical and shaped like sections of a sphere or paraboloid, freeform optics have complex, non-symmetrical surface geometries. This allows them to manipulate light in ways that are not possible with conventional optics. The freeform surface can be varied from only a few fringes of departure to a more radical shape depending on the application requirements.

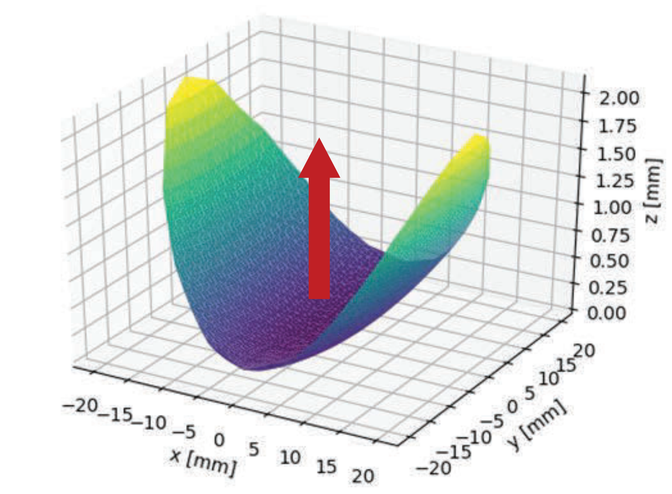
Often only a few microns of departure can have a significant impact and may significantly contribute to imaging applications.



$$z(x, y) = x^2 - y^2$$



$$z(x, y) = x^2 + y^2$$



$$z(x, y) = \frac{x^2}{{R_x}^2} + \frac{y^2}{{R_y}^2}$$

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Advantages of Freeform Mirrors in Optical System Design

Freeform mirrors allow optical designers to step beyond the limitations imposed by spherical symmetry, offering several key advantages:

- **Aberration Correction:** Tailored geometries allow for correction of field curvature, astigmatism, and other aberrations, especially in wide field-of-view or compact systems.
- **System Miniaturization:** Designers can combine multiple optical functions into a single element, reducing component count, size, and weight.
- **Improved Performance:** With precise control over light paths, freeform mirrors can improve throughput, resolution, and signal-to-noise ratios.
- **Mechanical Integration:** Using optical replication, optical and mechanical features can be designed into a single monolithic component, simplifying alignment and assembly.

These benefits make freeform optics ideal for a wide range of demanding applications, from compact spectrometers and fluorescence imagers to satellite payloads and endoscopic imaging systems.

Challenges with Traditional Manufacturing Techniques

Despite the clear benefits, freeform mirrors have historically been difficult and expensive to manufacture. Common production techniques include:

- Diamond Turning: High precision, but slow and costly for complex or off-axis geometries.
- Magnetorheological Finishing (MRF): Offers excellent surface quality but is typically used for low-volume, high-cost optics.
- Manual Polishing: Labor-intensive, inconsistent, and poorly suited to replication or tight tolerances.
- Glass or Plastic Molding: Suitable for high-volume, but limited by surface complexity and optical performance.
- **Nanoprint Lithography**

These methods typically involve long lead times, expensive tooling or labor, and are difficult to scale economically. As a result, their use in high-volume imaging products has been limited.

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Spectrum Scientific's Solution: Optical Replication for Freeform Mirrors

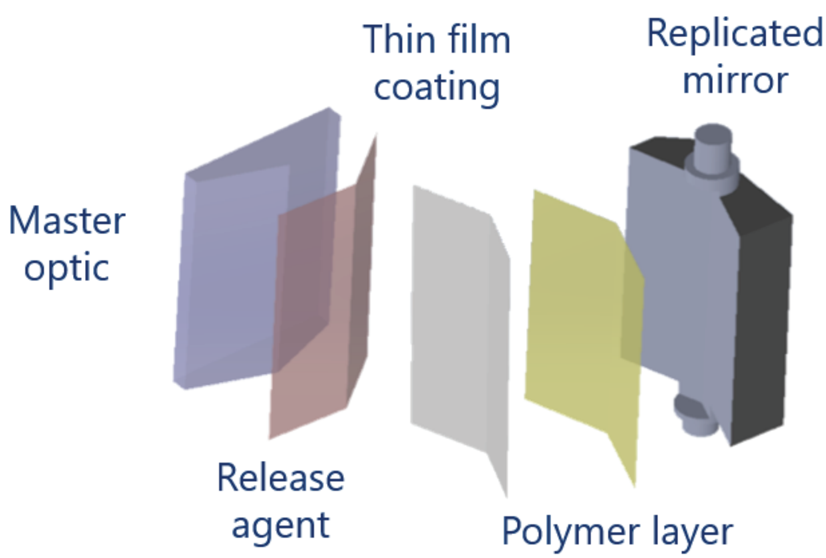
The Replication Process

SSI's optical replication process addresses the fundamental challenge of scaling freeform mirror production. The method involves:

- **Master Fabrication**: A high-precision optical master is created using diamond turning, polishing, or other traditional methods.
- **Mould Preparation**: The master is coated and prepared as a mould. Alignment features and reference datums may be incorporated at this stage.
- **Substrate Coating and Moulding:** A substrate is coated with a replication material and pressed against the master.
- **Curing and Separation:** The replicated surface is cured and released, producing a faithful copy of the master optic.

Coating and Finishing: Reflective coatings are applied, and fiducials can be added to facilitate alignment and system integration.

This process is similar in principle to nanoimprint lithography and offers exceptional precision and repeatability.



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Design and Manufacturing Best Practices

To ensure success during the design-to-manufacture transition, communication between designers and manufacturers is essential.

Recommended Design Inputs:

- **Complete surface equation and all coefficients**
- **Optical and mechanical tolerances**
- **Alignment fiducials and mechanical datums**
- **SAG tables for metrology comparison**
- **Environmental requirements (e.g., temperature range, vibration resistance)**

Both designer and manufacturer should use consistent references to ensure alignment across design, manufacturing, and assembly stages.

Metrology for Freeform Surfaces

Metrology plays a critical role in ensuring the quality of replicated freeform optics.

Different methods are available based on surface complexity and required accuracy:

- **Contact Probes:** Simple but may lack resolution and can damage soft or coated surfaces.
- **Interferometry:** Highly precise; ideal for freeforms when used with null correctors or computer-generated holograms.
- **Non-Contact Profilers:** Provide 3D surface maps and are ideal for verifying complex geometries.

For replicated optics, the master optic is measured to nanometre-level precision, ensuring that each copy maintains fidelity without requiring full remeasurement.

This drastically reduces inspection time and cost for high-volume production.

The choice of metrology is independent of the manufacturing process. Instead, the surface profile requirements of the freeform optic in question will determine the measurement methods used.

For optical replication, the masters are measured to a very high level of detail, using nanometre-level precision. However, this may not be necessary during the final production stages.

Freeform optics are more susceptible to alignment errors, compared to conventional optics. Whereas most aspheric surfaces are measured using interferometry using first-principal methods where point sources and plane wave interferometry can be used in all the wavefront, freeforms do not have this advantage.

Metrology for Freeform Surfaces cont...

Therefore, fiducials and reference datums are critical for angular and linear coordinates, where the manufacturer will use these for production and test purposes, while the end user will rely on fiducials for system integration.

Freeform Optics Manufacturing Method Comparison:

Manufacturing Method	Precision	Cost (Per Unit)	Tooling Cost	Volume Scalability	Design Flexibility	Surface Quality	Notes
Diamond Turning	High	$$$$	$	Low	High	Excellent	Best for prototypes and masters
Magnetorheological Finishing (MRF)	Very High	$$$$	$$	Low	Medium	Excellent	Used for ultra-precise surfaces
Conventional Polishing	Medium–High	$$$	$	Very Low	Medium	Variable	Time-consuming and skill-dependent
Glass Molding	Medium	$$	$$$	High	Low	Good	Best for small optics, simple shapes
Plastic Injection Molding	Low–Medium	$	$$$$	Very High	Low	Fair	Good for low-cost, non-critical optics
Nickel Electroforming	Medium	$$	$$	Medium	Limited	Good	Suitable for reflective surfaces
Optical Replication	High	$$	$	High	High	Excellent	Best for scalable, cost-effective precision optics

Replication can deliver surface figures as precise as $\lambda/10$, depending on the master. Part-to-part and batch-to-batch consistency are exceptional, making it ideal for OEM systems that require reliable optical performance across hundreds or thousands of units.

Production Scalability and Cost Savings

Replication significantly reduces both per-unit cost and production time. While traditional methods may take hours to fabricate a single optic, replication can produce dozens of parts per day from a single master.

- **No additional capital equipment required for ramp-up**
- **Unit costs as low as a few hundred dollars**
- **Consistent results across production cycles**
- **Flexible substrate choice for thermal stability or custom alignment**

The **replication layer smooths out substrate imperfections**, meaning lower-grade blanks can be used, reducing material and machining costs

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Conclusion: Unlocking the Potential of Freeform Optics

Spectrum Scientific's optical replication process transforms the economics of freeform mirror production. By enabling scalable manufacturing of high-performance optics with minimal variation, OEMs can integrate freeform surfaces into commercial imaging systems without the traditional cost and complexity.

Whether you're developing a next-generation spectrometer or an advanced diagnostic imaging device, optical replication offers a clear path forward—delivering precision, repeatability, and value at scale.

About Spectrum Scientific

Spectrum Scientific, Inc (SSI) has been manufacturing high volume flat, aspheric and freeform reflective optics, hollow retroreflectors and holographic diffraction gratings since 2004.

We primarily use the optical replication process allowing us to supply high fidelity, high specification precision optics at a lower cost compared to traditional volume manufacturing.

One of our key capabilities is the manufacture of freeform optics, off-axis paraboloids and ellipsoid mirrors with surface figures down to λ/10 or better. We also manufacture plane, concave and convex holographic diffraction gratings, which can be supplied as blazed gratings using our proprietary blazing technique, which not only offers high efficiency in the UV, but lower stray light compared to conventional ion etched gratings.

Spectrum Scientific is ISO 9001:2015 certified and RoHS compliant and our production and test areas are space qualified offering a silicone free production environment where we can replicate reflective optics for space borne telescopes and optical interconnect systems.

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