

**DEVELOPMENT OF ULTRA-PRECISION MACHINING  
PROCESS FOR MANUFACTURING OF FREEFORM  
OPTICAL SURFACES**

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**CENTRE FOR SENSORS, INSTRUMENTATION AND CYBER-  
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**INDIAN INSTITUTE OF TECHNOLOGY DELHI**

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OPTICAL SURFACES**

by

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**CENTRE FOR SENSORS, INSTRUMENTATION AND CYBER-PHYSICAL  
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Submitted

in fulfilment of the requirements for the degree of Doctor of Philosophy

to the



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*Dedicate to my family and teachers....!*

## Certificate

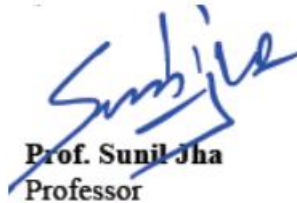
This is to certify that the thesis entitled “**DEVELOPMENT OF ULTRA-PRECISION MACHINING PROCESS FOR MANUFACTURING OF FREEFORM OPTICAL SURFACES**” submitted by **VINOD MISHRA** to the Centre for Sensors, Instrumentation and Cyber-physical Systems Engineering (SeNSE), Indian Institute of Technology Delhi for the award of the degree of **DOCTOR OF PHILOSOPHY**. This thesis is a bonafide record of the research carried out by him under our guidance and supervision. In our opinion the thesis has reached the standards fulfilling the requirements for the submission relating to the degree.

The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.



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**Vinod Mishra**

## Abstract

This research aims to solve the fabrication issues that restrict the surface quality of freeform optics during ultra-precision diamond turning. Freeform optics is a promising substitute for conventional optics in many applications, such as illumination applications, projection devices, ophthalmic applications, aerospace engineering, etc. The use of freeform optical elements in an optical system provides opportunities for numerous improvements in their optical performance at reduced system size, fabrication effort, and cost. Various fabrication methods viz. Ultra-precision machining, precision grinding, and advanced polishing methods are developed recently to fabricate freeform optical components. Ultra-precision machining is the best-suited method to process complex shapes with nano-metric surface finish and sub-micron profile accuracy. Slow tool servo (STS) configuration of ultra-precision machining is used to develop continuous type freeform surfaces. The low spindle speed of the STS process and involvement of multiple process parameters limit the surface quality. In principle, the optimized STS machining process is capable of developing the surface quality required for optical applications if supported by suitable metrology feedback. The metrology feedback is essential to correct the tool path to compensate for the form error. However, in the absence of a suitable metrology technique, it is not possible to achieve the desired surface quality. The alignment of freeform optics is another challenging task that affects both the fabrication and measurement process. It is essential to mount the freeform surface precisely with some pre-defined references during fabrication and metrology. The misalignment errors mislead the metrology feedback and limit the compensation process. Even if all these issues are resolved, a sustainable approach to fabricate the freeform optics is required. Till now, molding is the most suitable process for mass production of freeform optics. However, it is difficult to cut the hard mold materials in STS configuration due to low cutting speed. Polishing is one of the essential steps in that case, which significantly increases the process cost.

The thesis presents the development of the process for the fabrication of freeform optics by ultra-precision machining and is summarized in the following four major investigations:

- a) Optimization of STS process parameters *i.e.*, Machine axis motion increments, tool nose radius, spindle speed and depth of cut.
- b) Form error compensation technique for corrective machining of freeform optics.
- c) Novel alignment method for freeform optics
- d) Development of cost-effective polishing setups for finishing of freeform mold

In the first study, a set of experiments are performed to explore the effects of various process parameters of STS machining. The effects of tool setting in terms of tool overhang on surface quality and the selection of other parameters are studied. Further, the STS machining process parameters are analyzed and optimized. This initial study is helpful to fabricate the freeform optical surface with optimized process parameters.

In the second study, the tool path compensation routine is developed to minimize the form error. The fabrication steps of STS machining are discussed, including fiducial-based alignment of freeform optics, contact profiler based metrology and feedback mechanism to modify the tool path. The simulation study is also performed to understand the effects of alignment errors, which are the main reasons limiting the compensation cycle.

After understanding the reasons behind the saturation of the tool path compensation process, the third study is performed to solve the alignment issues. The sampling moiré based technique is developed to precisely align the freeform optics throughout the fabrication iterations. The proposed alignment technique is better than mechanical probe-based methods, easy to use, and cost-effective. The freeform surface with form accuracy  $0.18 \mu\text{m}$  is developed, which demonstrates the effectiveness of the alignment process. In the end, the overall alignment strategy is formulated to standardize the alignment process.

In the fourth study, the goal was to develop the mold insert for freeform optics. The flexible pad polishing setup is developed to improve the surface finish of freeform surfaces without affecting the profile. The precisely milled freeform surface of mold steel is polished on the developed setup. A significant improvement in the surface finish is achieved. Although the setup is used on a two-axis diamond turning machine, no substantial effect is found on the profile. Hence, the current setup can easily be used with STS configuration and other shape generation platforms also. Further, the magneto-rheological finishing and bonnet based hybrid polishing setup is designed for corrective polishing of the freeform surface. The capability of the setup is demonstrated by initial experiments and proposed as cost-effective solution for corrective polishing of freeform optics in the future.

It is expected that the investigations carried out in the thesis work will help in substantially increasing the accuracy of the production of high-performance freeform optics.

## सार

इस शोध का उद्देश्य ऐसे निर्माण मुद्दों को हल करना है, जो परिशुद्ध मशीनिंग के दौरान फ्रीफॉर्म ऑप्टिक्स की सतह की गुणवत्ता को अवरोधित करते हैं। फ्रीफॉर्म ऑप्टिक्स कई प्रयोगों में पारंपरिक प्रकाशिकी के लिए एक आशाजनक विकल्प है, जैसे कि रोशनी अनुप्रयोगों, प्रक्षेपण उपकरणों, नेत्र अनुप्रयोगों तथा एयरोस्पेस इंजीनियरिंग आदि। फ्रीफॉर्म ऑप्टिक्स का उपयोग करने से ऑप्टिकल सिस्टम की गुणवत्ता में सुधार होने के साथ-साथ, इसके साइज, निर्माण के मूल्य तथा लागत में भी कमी होती है। नैनोमेट्रिक-रफनेस सतह तथा सह-माइक्रोन प्रोफाइल सटीकता के साथ जटिल आकृतियों को संसाधित करने के लिए परिशुद्ध मशीनिंग सबसे उपयुक्त विधि है। परिशुद्ध मशीनिंग के स्लो टूल सर्वो (एसटीएस) कॉन्फिगरेशन का उपयोग फ्रीफॉर्म सतहों को विकसित करने के लिए किया जाता है। एसटीएस प्रक्रिया की कम गति में कटिंग और कई तरह के प्रक्रिया मापदंडों की भागीदारी सतह की गुणवत्ता को सीमित करती है। सतह की त्रुटियों को कम करने के लिए मेट्रोलाजी की फीडबैक आवश्यक है। हालांकि, एक उपयुक्त मेट्रोलाजी तकनीक की अनुपस्थिति में, वांछित सतह गुणवत्ता को प्राप्त करना संभव नहीं है। फ्रीफॉर्म ऑप्टिक्स का संरेखण एक और चुनौतीपूर्ण कार्य है जो निर्माण और माप प्रक्रिया दोनों को प्रभावित करता है। मिसएलाइनमेंट त्रुटियां मेट्रोलाजी फीडबैक को भ्रमित करती हैं और सतह गुणवत्ता की क्षतिपूर्ति प्रक्रिया को सीमित करती हैं। फैब्रिकेशन और मेट्रोलाजी के दौरान कुछ पूर्व-निर्धारित संदर्भों के साथ फ्रीफॉर्म सतह को ठीक से माउंट करना आवश्यक है। यहां तक कि अगर इन सभी मुद्दों को हल किया जाता है, तो भी फ्रीफॉर्म ऑप्टिक्स के निर्माण के लिए एक स्थायी दृष्टिकोण की आवश्यकता होती है। फ्रीफॉर्म ऑप्टिक्स के बड़े पैमाने पर उत्पादन के लिए मोल्डिंग सबसे उपयुक्त प्रक्रिया है, किंतु कम काटने की गति के कारण एसटीएस कॉन्फिगरेशन में ठोस मोल्ड पदार्थों को काटना मुश्किल है। पॉलिशिंग उस मामले में आवश्यक कदम है, जो प्रक्रिया लागत को काफी बढ़ाता है।

यह शोध परिशुद्ध मशीनिंग द्वारा फ्रीफॉर्म ऑप्टिक्स के निर्माण की प्रक्रिया के विकास को प्रस्तुत करता है। इस शोध के चार प्रमुख उद्देश्य निम्नलिखित हैं-

- अ) एसटीएस प्रक्रिया मापदंडों का अनुकूलन
- ब) फ्रीफॉर्म ऑप्टिक्स की फॉर्म त्रुटि में सुधार करने की तकनीक को विकसित करना
- स) फ्रीफॉर्म ऑप्टिक्स के लिए नवीन संरेखण विधि को विकसित करना
- द) फ्रीफॉर्म मोल्ड के लिए लागत प्रभावी पॉलिशिंग सेटअप का विकास करना।

पहले अध्ययन में, एसटीएस मशीनिंग के विभिन्न प्रक्रिया मापदंडों के प्रभावों का पता लगाने के लिए प्रयोग किए गए हैं। यह प्रारंभिक अध्ययन अनुकूलित प्रक्रिया मापदंडों के साथ अच्छी ऑप्टिकल सतह का निर्माण करने में सहायक है। दूसरे अध्ययन में, फॉर्म त्रुटि को कम करने के लिए तकनीक विकसित की गई है तथा एसटीएस मशीनिंग के निर्माण चरणों पर चर्चा की गई है। फॉर्म त्रुटि में सुधार के लिए विकसित की गई तकनीक में अवरोध करने वाले कारणों को समझने के बाद,

संरेखण मुद्दों को हल करने के लिए तीसरा अध्ययन किया गया है। सैंपलिंग मोडरे आधारित तकनीक को फैब्रिकेशन पुनरावृत्तियों में फ्रीफॉर्म ऑप्टिक्स को ठीक से संरेखित करने के लिए विकसित किया गया है। प्रस्तावित संरेखण तकनीक पारंपरिक संरेखण तकनीकों से आसान तथा लागत प्रभावी है। संरेखण तकनीक को प्रयोग करके फ्रीफॉर्म ऑप्टिक्स की फॉर्मसटीकता 0.18 माइक्रोन प्राप्त की गई, जो संरेखण प्रक्रिया की प्रभावशीलता को प्रदर्शित करता है। चौथे अध्ययन में, फ्रीफॉर्मऑप्टिक्स के लिए मोल्ड इंसर्ट को विकसित करने का लक्ष्य रखा गया था। प्रोफाइल को प्रभावित किए बिना फ्रीफॉर्म सतहों की रफनेस कम करने के लिए फ्लैक्सिबल पॉलिशिंग पैड सेटअप को विकसित किया गया है। वर्तमान सेटअप को आसानी से एसटीएस कॉन्फिगरेशन और अन्य प्रकार के सीएनसी प्लेटफार्मों के साथ भी उपयोग किया जा सकता है। इसके अलावा, मैग्नेटो-रियोलॉजिकल फिनिशिंग और बोनट आधारित हाइब्रिड पॉलिशिंग सेटअप को भी विकसित किया गया है। सेटअप की क्षमता को प्रारंभिक प्रयोगों द्वारा प्रदर्शित किया जाता है और भविष्य में फ्रीफॉर्म ऑप्टिक्स के सुधारात्मक निर्माण के लिए लागत प्रभावी समाधान के रूप में प्रस्तावित किया जाता है। यह उम्मीद की जाती है कि किया गया शोध उच्च-प्रदर्शन फ्रीफॉर्मऑप्टिक्स के उत्पादन की सटीकता को बढ़ाने में मदद करेगा।

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## List of abbreviations

ANOVA	Analysis of Variance
AFM	Atomic Force Microscope
CCI	Coherence Correlation Interferometer
CGH	Computer Generated Hologram
CIP	Carbonyl Iron Particles
CMM	Coordinate Measuring machine
CMP	Chemical Mechanical Polishing
DMM	Diamond Micro-Milling
FTS	Fast Tool Servo
IBF	Ion Beam Figuring
LWIR	Long Wave Infrared
MAF	Magnetic Abrasive Finishing
MRF	Magneto Rheological Finishing
MWLI	Multi-Wavelength Interferometer
PGI	Phase Grading Interferometer
PMD	Phase Measuring Deflectometry
PMMA	Polymethylmethacrylate
PSD	Power Spectral Density
S/N	Signal to Noise Ratio
SEM	Scanning Electron Microscope
SHS	Shack-Hartmann Sensor
STS	Slow Tool Servo