

INVESTIGATIONS ON METROLOGY OF
FREEFORM OPTICS AND ITS APPLICATION IN
INFRARED IMAGING

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APPLICATION IN INFRARED IMAGING**

by

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Engineering (SeNSE)**

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CERTIFICATE

This is to certify that the thesis titled **INVESTIGATIONS ON METROLOGY OF FREEFORM OPTICS AND ITS APPLICATION IN INFRARED IMAGING**, submitted by **LALIT MOHAN PANT (2014IDZ8184)**, to the Indian Institute of Technology, Delhi, for the award of the degree of **DOCTOR OF PHILOSOPHY**, is a bona fide record of the research work done by him under our supervision. 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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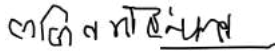
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JAI HIND


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ABSTRACT

This thesis is a result of the research work carried out at Centre for Sensors, Instrumentation, and Cyber-Physical Systems Engineering (SeNSE), Indian Institute of Technology (IIT) Delhi, and the Instruments Research and Development Establishment (IRDE), Dehradun. The precision optical systems are mostly developed using spherical optical components. However, these surfaces introduce inherent aberrations, which can be compensated either by using multiple spherical surfaces or by systems developed using aspherical or freeform optics. The freeform optical surfaces are non-rotational symmetric surfaces and are advantageous as they provide additional degrees of freedom to minimise optical aberrations, enhance the performance of the optical system, and make the system more compact by reducing its size, weight, and volume. Particularly for non-imaging applications, like solar concentrators, energy research, and the illumination industry, freeform optics have played an important role in system development. The complexity of the freeform surface increases with the increase of departure from the best-fit sphere. The required surface accuracy for the optical system is better than 100 nm or even less, particularly when the application area shifts towards a shorter wavelength region. The optical systems developed using freeform surfaces can be classified into two categories viz. non-imaging and imaging applications. Freeform surfaces are more difficult to manufacture and characterise due to their non-rotational, symmetric nature. Freeform optics can be manufactured using various processes such as precision machining, computer numerical control (CNC) grinding, and single point diamond turning (SPDT). All these processes need multi axis machining capabilities in order to fabricate freeform profiles. CNC polishing is a deterministic process of material removal based on the dwell time map. It allows a higher removal rate by spending more time in the zones of the work piece. Due to the complex geometries of the freeform surfaces, subaperture polishing is required across the entire surface in raster or spiral mode. The freeform surfaces can be generated and polished using zonal subaperture polishing by controlled removal of the material and monitored by a suitable metrology feedback mechanism. The available metrology techniques are broadly categorised into three classes such as probe based metrology viz. contact and non-contact profilometry, slope or curvature-based non-interferometric techniques, and non-null and null interferometry. These metrology techniques are well established for symmetric spherical surfaces but are not suitable for non-symmetrical surface metrology. Each metrology technique has its own inherent advantages and limitations. Interferometry is the best metrology tool for plane and spherical wavefronts, but it has major limitations for aspheric and freeform metrology as it requires a specific null corrector for the surface under test and is very expensive. In the case of aspheres, freeforms, and large size surfaces,

stitching techniques with null based metrology are being used. Recently, a Shack–Hartmann sensor (SHS) non-null slope measurement scheme has been reported for freeform metrology. The scheme utilises a subaperture stitching algorithm for the measurement of a freeform wavefront in transmission as well as in reflection mode. The accuracy of the measurement technique is limited by the alignment accuracy of subapertures with respect to the reference subaperture before the stitching process. In addition to all the methods being developed, there is a requirement to develop simple, low cost, easy-to-use, and versatile precision metrology techniques for freeform surfaces.

The present research work focuses to improve the accuracy of stitching errors by developing an intrinsic surface feature based technique for precise registration of subapertures and by developing a genetic algorithm (GA) based optimisation technique to improve the stitching accuracy. Subsequently development of a single shot, low cost freeform metrology using holo-shear lens based shearing interferometry. In addition, development of a cubic freeform optics for imaging applications. The research goal for this thesis was achieved by the following major activities.

1. Intrinsic surface feature based lateral misalignment correction for subaperture stitching metrology.
2. Experimental investigation of a single shot metrology of freeform optical wavefront using a holo-shear lens.
3. Investigation of GA based technique for subaperture stitching.
4. Development of a cubic freeform optics for wavefront coding application in infrared imaging.

The first chapter presents an overview of freeform optics requirements, benefits, and applications in modern optical systems. The challenges involved in the design, fabrication, and metrology of freeform optics and the current status of freeform metrology techniques are discussed. The manufacturing techniques for freeform surface generation and limitations for achieving precision manufacturing tolerances are discussed. The manufacturing of freeform optics is limited by the metrology for the error compensation of the surface profile. A survey of various metrology techniques for the testing and evaluation of freeform surfaces is explained.

The second chapter presents the basic principles of intrinsic surface feature (ISF) and lateral misalignment error correction for precision alignments between subapertures to enhance stitching accuracy. The intrinsic features are a very important signature of any surface and can be used as a precise alignment tool for subapertures, resulting in improved stitching accuracy. The Gaussian curvature is one of the intrinsic features that has a peculiar peak as per the geometry of the surface profile. Any shift in the peaks of the Gaussian curvature of reference and measured subaperture corresponds to lateral misalignment in the X and Y

directions and needs to be corrected for better registration of the subapertures into the global frame of reference prior to the stitching. Numerical simulation studies and experimental investigations are carried out, and higher accuracy of stitching is achieved.

The third chapter deals with the development of a new metrology method for freeform wavefronts using holo-shear lens based slope measurement techniques. The holo-shear lens is a special optical component that produces lateral shear fringes. These shear fringes are analysed to compute the slope data needed to reconstruct the wavefront profile. Using the developed technique, measurements of spherical, cylindrical, and freeform wavefronts are conducted. The experimental investigations show that holo-shear lens (HSL) can be used as a measuring tool for conventional, asymmetric, and freeform wavefronts. By using the technique, full profile measurement of a freeform wavefront in one instant is possible. This measurement method is compact, robust, fast, and easy to use. This technique requires only low cost optical and mechanical components as compared to other standard methods.

The fourth chapter describes the application of a genetic algorithm (GA) for the stitching of subapertures of test wavefronts measured by interferometry and a scanning Shack-Hartmann sensor. The basic principles of the genetic algorithm, its methodology, and the experimental results of the subaperture stitching using GA are presented. It has been observed that the GA technique is more generic in nature and has the potential to be used for subaperture stitching without any complex mathematical computation.

The fifth chapter presents the process of developing a precision cubic surface on a germanium (Ge) substrate for wavefront coding application in infrared imaging (IR). The IR imaging systems are prone to thermally induced defocus as these systems are developed using high refractive index materials. These materials possess a high rate of change in refractive index with temperature. A wavefront coding application provides a potential solution to overcome thermally induced defocus in the imaging system. The key component for the wavefront coding is a cubic freeform surface, which makes the imaging system invariant to defocus for an appropriate range. The alignment process using geometrical fiducials has improved the generation and characterization of cubic profile in a smaller number of iterations. The design, fabrication, characterisation details of the cubic surface and the results of the experimental setup for wavefront coding for IR imaging are presented.

The sixth chapter presents the conclusions of the research work and the scope of future research.

सारांश

यह शोध-प्रबन्ध (थीसिस) सेंटर फॉर सेंसर्स, इंस्ट्रुमेंटेशन एंड साइबर-फिजिकल सिस्टम्स इंजीनियरिंग (सैन्स), भारतीय प्रौद्योगिकी संस्थान (आईआईटी) दिल्ली, भारत और यंत्र अनुसंधान एवं विकास संस्थान, (आईआरडीई, डीआरडीओ), देहरादून में किए गए शोध कार्य का परिणाम है। फ्रीफॉर्म प्रकाशीय सतहें लाभप्रद हैं क्योंकि वे प्रकाशीय विपथन को कम करने, प्रकाशीय प्रणाली के प्रदर्शन को बढ़ाने और आकार, भार और आयतन को कम करके प्रणाली को अधिक सुगठित बनाते हैं। फ्रीफॉर्म सतह का उपयोग करके विकसित प्रकाशीय प्रणाली को दो श्रेणियों में वर्गीकृत किया जा सकता है जैसे कि नॉन-इमेजिंग और इमेजिंग अनुप्रयोग। विशेष रूप से, नॉन-इमेजिंग अनुप्रयोगों के मामले में जैसे रोशनी उद्योग में फ्रीफॉर्म प्रकाशीकी ने एक महत्वपूर्ण भूमिका निभाई है।

अपने नॉन-रोटेशन सममित प्रकृति के कारण फ्रीफॉर्म सतहों का निर्माण और वर्गीकरण करना अधिक कठिन होता है। फ्रीफॉर्म प्रकाशीय सतहों की जटिलता, बेस्ट फिट गोलीय सतह की वक्रता-त्रिज्या से विभिन्न होने के कारण बढ़ जाती है। फ्रीफॉर्म प्रकाशीकी को विभिन्न प्रक्रियाओं जैसे प्रिसिजन मशीनिंग, सिंगल पॉइंट डायमंड टर्निंग (एसपीडीटी), कंप्यूटर न्यूमेरिकल कंट्रोल (सीएनसी) ग्राइंडिंग और सीएनसी पॉलिशिंग का उपयोग करके निर्मित किया जा सकता है। फ्रीफॉर्म सतहों की जटिल ज्यामिति के कारण, रास्टर या स्पाइरल मोड में पूरी सतह पर सब-अपर्चर पॉलिशिंग की आवश्यकता होती है, जिसकी उपयुक्त मापन(मैट्रोलोजी) प्रक्रिया तंत्र द्वारा निगरानी की जाती है।

उपलब्ध मापन तकनीकों को प्रायः तीन वर्गों में वर्गीकृत किया गया है जैसे कि प्रोब आधारित मापन, कॉन्टैक्ट और नॉन-कॉन्टैक्ट प्रोफाइलोमीटरी, स्लोप या वक्रता-आधारित नॉन-इंटरफेरोमेट्रिक तकनीक, नॉन-नल और नल इंटरफेरोमेट्री। प्रत्येक मापन तकनीक के अपने निहित लाभ और सीमाएँ हैं।

प्रायः सतह मापन तकनीकें सममित गोलाकार सतहों के लिए अच्छी तरह से स्थापित हो चुकी हैं लेकिन ये फ्रीफॉर्म सतह मापन के लिए उपयुक्त नहीं हैं। स्फेयर, फ्रीफॉर्म और बड़े आकार की सतहों के मामले में, नल आधारित मापन के साथ स्ट्रिचिंग तकनीक का उपयोग किया जा रहा है। इन विन्यासों के साथ मुख्य सीमा, स्पेसिफिक नल प्रकाशिकी और ट्रांसमिशन स्फेयर की आवश्यकता है जो कि हर सतह हेतु अलग बनाए जाते हैं तथा बहुत महंगे होते हैं। हाल ही में फ्रीफॉर्म मापन के शैक-हार्टमैन सेंसर (एसएचएस) आधारित स्लोप मापन नल योजना का प्रस्ताव रखा गया है। जिसमें फ्रीफॉर्म, वेवफ्रंट की माप के लिए एक सब-अपर्चर स्ट्रिचिंग एल्गोरिद्म का उपयोग किया जाता है। माप तकनीक की सटीकता स्ट्रिचिंग से पहले रिफरेन्स सब-अपर्चर के सटीक एलाइमेंट द्वारा सीमित है। फ्रीफॉर्म सतहों के मापन हेतु एक सरल, कम लागत, उपयोग में आसान और एक सटीक मापन तकनीक विकसित करने की आवश्यकता है।

वर्तमान शोध कार्य के लिए स्टिचिंग हेतु सब-अपर्चर के सटीक पंजीकरण को विकसित करके माप सटीकता में सुधार करना, सॉफ्ट कंप्यूटिंग पद्धति द्वारा स्टिचिंग गुणों की गणना करना, फ्रीफॉर्म प्रकाशीकी के मापन हेतु सिंगल शॉट, कम लागत वाली मापन तकनीक का विकास करना तथा फ्रीफॉर्म सतह का इन्फ्रारेड इमेजिंग में अनुप्रयोग करने का लक्ष्य रखा गया ।

इस शोध-प्रबंध के लक्ष्यों को प्राप्त करने के लिए निम्नलिखित प्रमुख कार्य किए गए हैं :

- (क) सबअपर्चर- स्टिचिंग के लिए इंटरैक्टिव सरफेस फीचर आधारित लेटरल मिस एलाइन्मेंट करेक्शन मापन का विकास ।
- (ख) होलोशियर लेंस का उपयोग करके फ्रीफॉर्म प्रकाशीय वेवफ्रंट के सिंगल शॉट मापन का विकास ।
- (ग) सबअपर्चर- स्टिचिंग के लिए जेनेटिक-एल्गोरिद्म आधारित तकनीक का विकास ।
- (घ) इन्फ्रारेड इमेजिंग में वेवफ्रंट कोडिंग अनुप्रयोग हेतु क्यूबिक फ्रीफॉर्म प्रकाशीकी घटक का विकास तथा प्रायोगिक परीक्षण ।

उपर्युक्त तकनीको से फ्रीफॉर्म सतहों के सटीक मापन तथा अनुप्रयोग में मदद मिलेगी ।

ॐ असतो मा सद्गमय । तमसो मा ज्योतिर्गमय । मृत्योर्मा अमृतं गमय ॥

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ABBREVIATIONS

CCD	Charge Coupled Device
CCP	Computer Controlled Polishing
CGH	Computer Generated Hologram
CMM	Coordinate Measurement Machine
CNC	Computer Numerical Controlled
CPC	Compound Parabolic Concentrator
DMD	Digital Micromirror Device
DMM	Deformable Membrane Mirror Device
DOE	Diffractive Optical Element
DTIRCs	Dielectric Totally Internally Reflecting Concentrators
EMD	Empirical Mode Decomposition
FFT	Fast Fourier Transfer
FIR	Far Infrared
FTS	Fast Tool Servo
GA	Genetic Algorithm
HHT	Hilbert Huang Transform
HMD	Head Mounted Display
HWP	Half Wave Plate
HSL	Holo-shear Lens
HT	Hilbert Transform
IBF	Ion Beam Figuring
IR	Infrared
ISF	Intrinsic Surface Feature
LWIR	Long-Wavelength
MWIR	Mid-Wavelength Infrared
MZ	Mach-Zehnder
NAT	Nodal Aberration Theory
NIR	Near Infrared
MRF	Magneto Rheological Finishing
MTF	Modulation Transfer Function
PBS	Polarising Beam Splitter
PDE	Partial Differential Equations
PMD	Phase Measuring Deflectometry

PMMA	Poly-Methyl Methacrylate
PSF	Point Spread Function
PV	Peak to Valley
RMS	Root Mean Square
SHS	Shack-Hartmann Sensor
SMS	Simultaneous Multiple Surface
SNR	Signal-to-Noise Ratio
SPDT	Single Point Diamond Turning
SSD	Sub-Surface Damages
STS	Slow Tool Servo
SUT	Surface Under Test
SWIR	Short-Wavelength Infrared
TG	Twyman–Green
TIR	Total Internal Reflection
TS	Transmission Sphere
TWI	Tilted Wave Interferometry
UPDTM	Ultra-Precision Diamond Turning Machining
UPM	Ultra-Precision Milling