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 profilometery, 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 on the improvement of the accuracy of freeform metrology by developing a technique for precise registration of subapertures for existing stitching processes and by developing a genetic algorithm (GA) based optimisation technique to improve the stitching accuracy. Further, to develop a single shot, low cost freeform metrology using holoshear lens based shearing interferometry. In addition, development of 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 application of the 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.