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Advances in the design and manufacturing of novel freeform optics

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Abstract
Freeform optics has become the most prominent element of the optics industry. Advanced freeform optical designs supplementary to ultra-precision manufacturing and metrology techniques have upgraded the lifestyle, thinking, and observing power of existing humans. Imaginations related to space explorations, portability, accessibility have also witnessed sensible in today’s time with freeform optics. Present-day design methods and fabrications techniques applicable in the development of freeform optics and the market requirements are focussed and explained with the help of traditional and non-traditional optical applications. Over the years, significant research is performed in the emerging field of freeform optics, but no standards are established yet in terms of tolerances and definitions. We critically review the optical design methods for freeform optics considering the image forming and non-image forming applications. Numerous subtractive manufacturing technologies including figure correction methods and metrology have been developed to fabricate extreme modern freeform optics to satisfy the demands of various applications such as space, astronomy, earth science, defence, biomedical, material processing, surveillance, and many more. We described a variety of advanced technologies in manufacturing and metrology for novel freeform optics. Next, we also covered the manufacturing-oriented design scheme for advanced optics. We conclude this review with an outlook on the future of freeform optics design, manufacturing and metrology.

Keywords: freeform optics, optical design, optical fabrication, ultra-precision machining, surface metrology

1. Introduction
Today, freeform is the emerging scope in the various kinds of optical systems. Surfaces that are axially unbalanced or have no axis of rotational invariance are known as freeform surfaces. The surface having a periodic and irregular shape concerning to its axis and surface textures are termed as the freeform surfaces [1, 2]. Freeform optics enhances the performance and efficiency of the systems in optomechanical and optoelectronic domains. It facilitates the elimination of errors or aberrations like spherical aberration, astigmatism, coma, distortion, chromatic aberration and provides excellent system integration. When such surface is applied to the optics, it provides numerous opportunities for optical designers and develops creative challenges for freeform optical fabrication and testing techniques. The freeform optical component provides advantages over traditional optical components and differs with many features as follows,
Enhancement of optical performance or maintains the same optical performance with a compact system, such as an expanded field of view (FOV) and aberration-free surfaces [3].

Quantitative reduction in optical components of systems reduces the overall cost [4].

Simplified assembly because of a few optical components. For example, freeform surfaces fabricated on a single monolith [5].

Miniaturization of optical systems [6].

Reduces the weight of optical system and making it compact [7].

Improving the capabilities of optical designers and innovation in optics [8].

Freeform optical surfaces are described in a variety of ways. These surfaces can be explained not only considering axis but also by types of surfaces as given below,

Mathematical formulated and design software modelled continuous surfaces. Examples: aspheric mirrors [9], cylindrical mirrors [10] and spiral mirrors [11].

Truncated design from the main profiles which are known as the discontinuous surface generally steps and facets on the surfaces. Examples: Fresnel lens for illumination applications [12].

Functional structured surface which has the specific application. Typical structured surfaces include various shapes such as pyramids, circular, and non-circular profiles on a surface in the form of an array. Example: retro-reflective micro-optical structure for automobile applications [13].

Multiple freeform surfaces on a single monolith. Example: prisms used in the head-up display [14] and spectrometer [15].

With recent advances in optical fabrication technologies such as computer numerical control subtractive, formative and additive manufacturing techniques, opto-mechanical systems are no longer constrained by the shapes and forms that can be produced, but rather by the typical solution proposed by optical and mechanical designers. Therefore, an urgent need of critical study on advanced designs, manufacturing, and production methods for the freeform optics is fulfilled by this article.

To meet the requirements of current market, process chains are dependent on the manufacturing types i.e. make-to-order, make-to-assemble and make-to-stock. Figure 1 provides an idea about the various branches that are associated with the development of freeform optics. Stages for generating and the advantages-cum need of the freeform optics helps to maintain the technology economical and accessible to every sector.

Our main aim in this review is to address certain questions like; What are our new understanding regarding freeform optics? At what stage we have reached in terms of developments and the applications of freeform surfaces in optical systems? How many efficient tools we have been developed in aspects of designs, fabrication, and production? What are the main challenges in freeform optics production? To provide the answers to these questions, we will first introduce the merits of freeform optics, followed by an overview of applications, design tools, fabrication, metrology, and massive production techniques.
2. Merits of freeform optics and applications

Typical applications have been developed based on different working principles and various freeform surfaces are designed and used in refractive, reflective and diffractive optical systems. Freeform optics has plenty of applications in various fields, such as applications of space, biomedical, solar energy, surveillance, defence, entertainment, training and many more. The freeform design in an optical application can be broadly categorized into non-imaging and imaging applications [23]. The differences in functionality of two types of optical systems are that the imaging optics explains about the intensity and location of the light whereas, the non-imaging optical system redistributes the energy [24]. Table 1 shows the classification of recently utilized freeform surfaces in various applications and their principles of functioning.

| Applications       | Functionalities                                      | Merits                                                                 |
|--------------------|------------------------------------------------------|------------------------------------------------------------------------|
| Non-image forming  | Concentration                                        | Concentration rate is increased by removing the spherical aberrations from the optical components |
|                    | Beam shaper                                          | Both irradiance and spatial wavefront distribution is controlled with high degree of freedom |
| Image forming      | Illumination                                         | Avoid restriction on the surface geometry                               |
|                    | Projector                                            | Reduce the projection distance for compact design of projector         |
|                    | Head mounted/worn display                            | Excellent high order aberration correction properties                  |
|                    | Infrared system                                      | High detection capability and optical path is folded drastically        |
|                    | Multiple degrees-of-freedom for correction of off-axis aberrations |                                                                 |

2.1. Non-image forming freeform surfaces

The non-imaging system is the important domain for the freeform optics. The freeform non-imaging optics focuses on the energy distribution and efficiency of the whole optical system. There are three basic elements of non-image forming systems i.e. source, optical element and the receiver. Freeform surfaces in these systems facilitates the transfer of light efficiently.

2.1.1. Concentration. Since the early 1990s, there are five designs available of concentrators; RR, XX, XR, RX, and RXI [24–28]. In these designs, the letters ‘R’, ‘X’, and ‘I’ represent refraction, reflection, and total internal reflection (TIR). Taking solar panel as an example, the principle is to transform the sun’s radiant energy into the thermal energy. Collecting the incident energy (light rays) from the very large incident aperture into a tiny exit aperture is generally adopted by the solar energy concentrators. There are more related optical losses with the higher number of concentrating components (i.e. receivers) used in the concentrating system, therefore the novel freeform surfaces, their designs, and new fabrication techniques are required which can minimize the losses [29]. The concentration geometric ratio is expressed as,

\[ C = \frac{Aa}{Ar} \]  

where \( Aa \) is aperture area and \( Ar \) is the receiver area. With the equation (1), it is possible to obtain high temperature at the collector outlet while decreasing the receiver area where the thermal losses occur [24]. Figure 2 shows the structure and design of the compound parabolic concentrator (CPC). It consists of two parabolic segments and the collector. This design is divided into three parts: incident aperture, internal reflective sides, and an exit aperture. The parallel beams of solar energy incident with respect to the centre axis of parabolic rims are concentrated at the focus of the parabola. The only disadvantage of CPC is that it requires the tracking system [30].

TIR is an optical phenomenon which takes place when the light rays travel from dense refractive index medium to low refractive index medium. The light ray reflects in the condition of incident angle less than the critical angle. The dielectric totally internally reflecting concentrators (DTIRC) uses the TIR properties of the dielectric medium and combines the front surface refraction with the TIR from the sides to obtain the concentrations up to theoretical maximum limits. There are two advantages of DTIRC over CPC, one is the higher concentration and the second is the smaller in size [33].

Although, the 2D geometries are simpler to the 3D geometries to be designed but they have less degree of freedom and less efficient to control the rays. Even if the selection of rays in 2D design is perfect, still it is not feasible to generate rotational or linear devices. The problem for 2D geometry concentrators is the curves for refraction and reflection phenomenon. First the simultaneous multiple surface (SMS) 2D was implemented for the 2D concentrator applications. Later, the SMS 3D design method was successful to design the curved freeform surfaces with more control over the rays [34]. Instituto de Energia Solar, Universidad Politecnica de Madrid in Spain, and Light Prescription Innovators have produced a variety of non-imaging concentrators based on SMS method [30, 35]. Mainly, design and manufacture were focused on renewable systems for generation of electricity with high-concentration photovoltaic systems (HCPV). With the use of Fresnel-Kohler technology in HCPV systems, the solar concentrators offered geometrical concentration of 1024X, high acceptance angle of ±1.1°, and high optical efficiency.
2.1.2. Beam shaping. Beam shaping is a method that redistributes the irradiance and the phase of an optical radiation beam. A light beam in general is defined by two quantities, one is irradiance spatial distribution and the second is phase spatial distribution also known as wavefront. So, the beam shaping process is to control these two quantities which involve at least two optical surfaces for wavefront tuning and irradiance [36]. This technology is applied to both coherent and incoherent beams. The shape of the beam such as rectangular, circular, Gaussian, and annular, is defined by the distribution of irradiance whereas the properties of the beam profile are determined by the phase of the beam. The laser beam shaping (LBS) has numerous applications such as lithography, printing, optical data/image processing, laser weapons, laser/material processing, and laser art patterns [37]. LBS techniques are classified into two categories: beam integrators and field mappers. The beam integrators can handle both multimode and coherent beams with unknown input field distributions and have a low sensitivity to beam alignment and size. The field mappers work for single-mode beams (i.e. beams with known field distribution) and they are generally highly sensitive to the size of the beams and alignment. Primarily in 1960s, the refractive beam shaping devices were invented and further these devices found extensive applications in laser systems [38–41]. The concept of a variable-power lens was given by Luis Alvarez. The design variable-power was described using a composite plano-spherical lens with lateral translation of the mutually inverted cubic surface optic elements [42].

Figure 3 illustrates the basic principle of the Alvarez type beam shaper and a miniaturized Alvarez lens element fabricated using the compression moulding. Here, the optics acts as optical-plate when positioned centre-to-centre and on providing the translational movement of each component in x-axis between \(-\delta\) and \(+\delta\) the optical power is changed. The optimal lens performance of each plano-freeform element (in Cartesian coordinates) is given by the equation (2),

\[
z = \sum_{k=1}^{n} Ai E_i (x, y)
\]

where \(x\) and \(y\) are freeform surface coordinates, \(Ai\) is the coefficient of the \(i\)th extended polynomial term \(E_i(x,y)\) and the total number of polynomial in series is denoted by \(n\) [43].
2.1.3. Illumination. The technique of illumination uses the light energy from single or multiple sources to obtain a constructive effect, such as in various lighting systems of automotive, outdoor, and indoor [45]. The principle of the illumination applications is to control the intensity distribution, based on this various light emitting diodes (LEDs) are designed and manufactured. LEDs also assist in road lighting as they consume less energy and produce fewer thermal effects to the environment. Freeform design for LEDs can enhance the surface luminance uniformity and spread the light in a controlled way on the road [46]. As shown in figure 4(a), the optical power of the LEDs are Lambertian distributed that has round light pattern. In this design of the road lights, middle portion of the illumination zone is brighter than the edges which results in the 50% loss of light energy off the road. It also creates eye-strain for pedestrians and drivers during dark and strictly act opposite to the green-lighting. The rectangular illumination zone is restricted to the dimensions of the road and matches the road perfectly as shown in figure 4(b). The freeform design for LEDs allows to spread the even light distribution over the road. Figure 4(c) shows the prototype of compact LED ultra-efficient aspherical lens developed using the direct design method that provides accurate control over the spatial energy distribution with circular illumination. Feng et al [46] developed a design method for road lighting optical system and solved the problem of glare of the luminaire. A freeform lens for rectangular illuminance distribution is designed by feedback modification method that improves the illuminance uniformity from 18.75% to 81.08% [47] and the prototype is shown in figure 4(d).

The freeform optics can also be used to control the angle of incident of laser beam in the optical lithography. The dipoles, quasar, annular and many more are some unique and special illumination patterns that are used in the optical lithography technique. Freeform lens array can enhance the energy efficiency, reduces the size of the illumination system, and complexity of the exposure system [50]. Another example of non-imaging optics with freeform surfaces are the light pipes. The freeform light pipes can be optimized to perform various functions such as efficient coupling between the light source and the receiver i.e. shaping and mixing of the light [51].

2.2. Image forming freeform optics

The optical performance in an imaging system is enhanced by reducing profile and form errors, expansion of the FOV, balancing the optical aberrations, and improvements in the depth of field. The imaging optical system consists of three main parts, the object, the optic, and the image of that object [45].

2.2.1. Projection. The principal of projectors is the image projection, and they produce large image of a small object.
Traditionally, the projection systems were functional with the long throw distance which consumed a large unutilized space. Also, the shadow was generated on the screen if any opaque object or presenter comes in between the projector device and the screen. Such type of demerit can be eliminated by the freeform projection systems as shown in figure 5. This schematic diagram illustrates the difference between the traditional projector and ultrashort distance projector with an external freeform component. To minimize the horizontal throw distance of a projector, freeform external mirror finds more suitable in terms of making the projection system compact in size. For example, the projection distance of 20–40 cm was reduced for an 80 inch screen using the external freeform projection mirror [52]. In general, the freeform surfaces used for projectors are smooth and continuous surfaces characterized by various analytical functions. The design concept of projection device with two external mirrors was given to provide ultrashort distance between the projector and the screen [53]. The throw distance for 78.3 inch screen was reduced from 200 cm to 48 cm and obtained a well-balanced image quality with low distortion.

Two techniques commonly used to optically configure the ultrashort projectors. Firstly, the combination of three or four spherical/aspheric mirrors with the large magnification objectives [54] and the other is to merge external optic with the regular projector [55, 56]. The challenges to achieve the larger display screen, low weight, compact size, high imaging projection performance, and ultrashort throw distance can be overcome with the introduction of freeform surfaces into projections systems.

2.2.2. Head mounted display (HMD). HMD is a visualization device made up by combination of the optical, mechanical, and electronic systems in a very compact area. These devices consists of a modulated light source with an electronic drive system, optomechanical assemblies such as housing, helmet, or frames of eyeglasses [57]. The pilots use the HMD visualizing every information of the aircraft position, altitude coordinates, various indicators at one display without disturbing to see through that optical system. This acts as the safety feature for the pilots when travelling at high speed and main concerns are to operate the aeroplane with all the controllers [58].

Emerging technologies such as miniaturized modulated laser light, micro displays unit, freeform projection optics, all research contributions have led HMD available for devices such as augmentation reality (AR)/virtual reality (VR), medical, biosensing, robotics controlling etc. With the involvement of freeform optics into the opto-mechanical assembly of HMDs, the size, weight, and even eyepiece optics have been replaced by the micro projection displays. The FOV is increased using the tiled optics technique that used in recent VR and AR devices [59]. Eye tracked optical see-through (OST) HMD has been developed and used as the assistive and augmentative communication device [60]. The distance from the eye to the display is shortened with the freeform optics. The optical performance such as image quality and FOV is not compromised while reducing the size till one-fourth of the total volume occupied in the conventional headsets [61]. Another OST HMD was designed, and prototype was developed that consists of a freeform lens, and freeform prism eyepiece as shown in figure 6 [62]. The optics is capable to
provide the virtual display path with an angular resolution of 1.8 arcminutes across a 40° diagonal field of vision, while the see-through view has a 0.5 arcminutes angular resolution. OST HMD have the advantages such as reduce fatigue, visual discomforts, and perceptual distortions with the multiple image planes.

2.2.3. Infrared (IR) imaging system. Human eyes are unable to sense IR waves, however instruments equipped with IR materials can detect the IR energy, allowing us to see the emitted thermal waves from warm objects [63]. The subdivision of IR spectrum are Far-IR within 15.0–1000 $\mu$m wavelength, long-wavelength 8.0–15.0 $\mu$m, mid-wavelength IR 3.0–8.0 $\mu$m, short-wavelength IR 1.4–3.0 $\mu$m, and near IR 0.7–1.4 $\mu$m [64]. Typical IR applications include night vision goggles, IR cameras, zooming systems, thermal spectroscopy and low earth orbiting spectrophotometers. IR cameras with wide rectangular FOV finds applications such as surveillance and military obstacle detection vehicle. Compared with a normal camera system work in spectral visible range, a large aperture is required when operating in IR range with the same observation range [65]. This large aperture will have the significant amount of aberration which will reduce the image quality [66]. To improve the image quality, an off-axis IR freeform reflective imaging system was designed with field expansion construction method. Utilization of freeform optics can also eliminate the chromatic aberration, and increase transmission [65].

Figure 7 shows the design layout, prototype and captured outdoor images from the IR camera that consists of off-axis optical elements with the short focal length. This off-axis IR imaging system consists of three mirrors configuration and a detector. The M1 and M2 are the freeform mirrors and M2 mirror have the aspherical surface. The function of the freeform surfaces is to avoid the beam obscuration, unconventional off-axis aberrations including field curvature and distortion and balancing the aberrations in both horizontal and tangential directions [67].
3. Design methods and optimizations of freeform systems

In this section, we present a comprehensive review of the various freeform design methods and their applications. Optical design is art and science of creating a system that meets a variety of requirements, including manufacturing limitations, cost, tolerances, and physical size. The freeform surfaces are the advanced surfaces that can support numerous functions in a single optical component. Designing is a promising strategy for improving the performance of functional surfaces by changing the traditional geometry to freeform shapes. The most common design tool are the computer-aided design (CAD) and finite element method implemented to design and optimization [68]. Computers are used to perform raytracing, calculations and evaluate the overall optical performances rapidly. Even with today’s high-speed computers and tremendous processing capacity, designer experience and directions are often considered as a prominent key to reach at an optimized design solution.

The design process includes descriptions of the object’s shape and type, the size of the optics, the component’s location in the system, and the materials required to allow the light energy beams to hit the required targets. Designing of freeform optics can be performed by following steps such as concept of design where the creation or selection of starting points with minimum aberrations, optical design using theoretical models and parametric values, optical ray simulations and output performance-based optimization with the help of commercial optical design software. Final design is obtained after performing these steps as shown in figure 8. The designing strategy are categorized in two ways, such as direct design methods [69, 70] which perform the calculation-based designing of geometrical and differential equations, and indirect design methods that rely on the existing designs or patents.

3.1. Partial differential equation (PDE)

In 1949, Wasserman and Wolf derived a differential equation used to achieve axial stigmatism and adequate solutions for any centred system designed with two aspheric surfaces in a sine condition [71]. A first-order or a second-order PDE is established to design a freeform surface through the PDE method. This method is dependent on the simultaneous solution of differential equations for desired shapes and profiles. PDE method can provide the designs for non-imaging and imaging optics with spherical, aspheric, and freeform surfaces. In 1957, Vaskas introduced a method that was an extended version of Wasserman and Wolf differential equations. For example, PDE method was provided for a more general situation where \( \sum \) and \( \sum' \) (i.e. two aspheric surfaces) were separated by the number of known surfaces [72] as given in equations (3) and (4).

\[
\sum : n (\cos \omega \cdot (dx/dt) + \sin \omega \cdot (dy/dt)) = n1 (\cos \omega1 \cdot (dx/dt) + \sin \omega1 \cdot (dy/dt)) \quad (3)
\]

\[
\sum' : nk + 1 (\cos \omega k + 1 \cdot (dx/dt) + \sin \omega k + 1 \cdot (dy/dt)) = n' (\cos \omega' \cdot (dx/dt) + \sin \omega' \cdot (dy/dt)) \quad (4)
\]

where \( \omega, \omega1, \omega k + 1, \omega' \) are the angle of incidence of a ray with \( \sum, \sum' \) aspheric surfaces and \( n, n1, nk + 1, n' \) are the refractive indexes.

The Wasserman-Wolf approach was only effective in the construction of 2D optics since it calculates discrete light. However, the factors like limitation of two optical surfaces and to axial symmetric system has made this design method limitedly adopted by the designers [73]. Knapp used the macro software technique to evaluate the new equations in 2002, using commercial software called Generalised Aspheric Design Program (GAP) to generate the designs for non-axially symmetric elements [74]. GAP has disadvantages such as a long time to arrive at a solution, not able to address the chromatic aberrations.

3.2. Tailoring method

Winston and Ries pioneered the tailoring method in 1993. Davies used the geometrical optics to test and verify the edge
ray principle in 1994 [75]. In this design process, it states that consideration should be done only of certain limiting rays also called as edge rays that provides the guaranteed transfer of all rays. For a system of multiple optical components such as series of lenses, there are additional edge rays to be considered, like the rays that are far away from the optical axis but have any specified angle within the acceptance angle. The compound elliptical concentrator reflector profile was obtained by solving the differential equation for a desired angular power distribution and a given source [76]. They were able to show a constant irradiance from $-43^\circ$ to $+43^\circ$ produced by a reflector using a cylindrical source of constant brightness. Jenkins and Winston developed a non-imaging optics integral design method based on this idea to offer compact and small reflector profiles by eliminating the requirement for a gap between the reflector profile and the source. It was reported that a tailored reflector design aided in the distribution of general illumination patterns onto surrounding target planes [77]. Researchers also reported the study on the tailored edge-ray designs method where they used light source of tubular form for the design of tailoring lighting reflectors by solving PDE [78]. Tailoring design method is also used to develop illumination system design, and to build 3D freeform surfaces by solving nonlinear PDEs. The relationship between light vectors such as incident, normal, and exit, as well as constraints among the source of light with the irradiance distribution at the reference surface, are taken into account by the formed freeform optical surface [79].

Tailoring an optical surface is the process of translating desired optical qualities into a differential equation, which is numerically solved to determine the geometry of the optical surface. When it comes to designing freeform optical surfaces for lighting applications, optimization processes suffer from the fact that a good representation of optical surfaces usually involves a large number of parameters such as transfer of light equipment’s, illuminance, angular size of target area, uniformity, incidence and reflection/refraction angle of beams, beam source, size of the system and many more. Even tiny modifications in the surface form might can cause significant changes in the irradiance distribution produced. Most of the design methods focus on producing the prescribed irradiance distribution on the planar targets. Feng et al introduced an iterative wavefront tailoring method for curved targets. This method is created using a stereographic projection coordinate system that used a unique source domain coordinate transformation. This approach solves the design of illumination problems for 3D surface lighting i.e. in cultural relics, sculptures surface and surface of the roads mountains [17]. Figure 9 is a concept design freeform illuminations application. The point source is at origin that emit light in right half space, inner surface is spherical, outer surface is the freeform denoted as $(x_f, y_f, z_f)$ and the curved target is described as $(x, y, z)$. The challenge in tailoring method is complexed mathematical calculations and method is not suitable for more than two freeform surfaces.

### 3.3. Point-to-point mapping

Parkyn presented point-to-point mapping for lighting operations with non-rotationally symmetrical optics in 1998 [80]. The point-to-point mapping is achieved using the concept of energy conservation from the lighting energies of source and at the target. Mapping method determines the final shape of freeform optics by executing iterations of the point’s normal vectors and coordinates. Figure 10 depicts the mapping approach in which the $S$ source is at the orthogonal coordinate system’s origin. The freeform optic $p$ is located as $(\theta, \phi, \rho)$ on spherical coordinate system with the normal vector $N$ and incident light vector $I$ at $p$.

Division of optics surface into the grids are used to arrange the source and target surfaces. By determining the optic’s normal vector, extrinsic differential geometry provides the relationship between these grids in order to produce a smooth
surface. Each grid has many cells having specific angles so that every cell has the same luminous flux. Based on this design technique and intensity distribution of the source, the other grid with the same features such as the angle, shape and number of cells are formed. Likewise, a freeform reflector for illumination application was designed using mapping of equi-flux grids between a point source and a target [81]. This design technique uses the point-cloud [82] to describe the surface shapes and follows the laws of optics for ray-trace for performance evaluation of the optical systems. The limitation of mapping method is that only one freeform surface can be designed or calculated and approximated calculation for extended light source.

3.4. Simultaneous multiple surface (SMS) method

In 1990 [24], a breakthrough was made in the design of optics by Minano and Benitez where they proposed a design method for 2D non-imaging optics. SMS enables the designs of multiple optical surfaces concurrently. Using the SMS method [83] for two-dimensional optics, a wide variety of rotational symmetric components and compact devices were developed with close tolerances to the theoretical limit. The maximum possible concentration [45, 84] is given by the equation (5),

$$C_{3D} = \frac{n^2}{\sin \theta^2}$$  \hspace{1cm} (5)

where $n$ is the refractive index of concentrator medium and $\theta$ is the half angle of acceptance. This design method is found to be applicable in both imaging and non-imaging applications specifically for developing 3D optical systems for concentrated solar power [85]. SMS design method is simple, and efficient [86] with the principle of prescribed irradiance and bundle coupling. Any ray of input bundle $M_i$ is entering the optical component pass through as the ray of output bundle $M_o$ and vice versa, making both the bundles with the same ray is known as bundle coupling i.e. same bundle $M_c = M_i \cap M_o$. Whereas the prescribed irradiance is stated as one bundle paired in another bundle for example, SMS links both the two wavefronts i.e. input into output.

SMS principles are depicted in figure 11. Simultaneous creation of two freeform optical surfaces is achieved by SMS 3D method. Normal congruencies $W_{i1}$ and $W_{i2}$ are converted to $W_{o1}$ and $W_{o2}$ normal congruencies [86]. This method is capable to calculate the point source and the extended light source. The difference between the SMS and mapping methods is that SMS takes into account small bundles of rays whereas mapping method uses a large batch of feature rays. The Fermat’s light principle is also used in this method to incorporate angle and source size into calculations [87]. Unlike the SMS comparing the local angles against the ideal angles for the all-surface points, another design strategy is proposed for freeform surfaces named as vector method that uses Snell-Descartes’ law and Fermat principle [88]. This freeform design technique is based on ideal interfaces i.e. compares the local normal against the ideal normal.

3.5. Aberration theory based

The aberration fields of the optical systems made of rotational symmetric components are generally described by the nodal aberration theory (NAT), developed by the Shacks and Thompson [90, 91]. NAT is used to study the errors based on the image field and subsequently eliminate the aberration by the changing the design parameter values. NAT mathematically works on the misalignments entities such as tilts and decentres to sum up the displaced aberration fields produced by the surfaces in action. In the FOV, nodes are points at which the sum of displaced aberration fields cancels. The whole optical element is divided into subsystems, but the freeform surface cannot, hence NAT is extended for freeform surfaces. Fuerschbach et al developed NAT for optical systems with freeform surfaces [92], although the freeform surfaces described using Zernike polynomials are not the universal balancing solutions for every type of aberrations. Aberration theory based design method [93] is most systematic strategy.
to obtain the finest solutions for a freeform system. This approach aids us to understand the high-order polynomials and Zernike terms contributions and future predictions to balance the aberrations in the optics systems. For example, in an unobscured geometry, the main aberrations are defocus, astigmatism and coma that fluctuates when corrective Zernike terms are added/changed. Such as these high magnitude aberrations likely to be field dependent. The coma surface if added after stop can induce the foci plane tilt. NAT based designing is found to be more flexible to the experienced designers as it requires deep mathematical understanding of the aberrations.

Zheng et al. [94] presented a direct design method for off-axis reflective cylindrical imaging system that consider manufacturing constraints during the freeform optical design. This design approach employs two stages i.e. construction stage and iteration stage. In construction stage, the feature rays and feature points on it are defined to form freeform surface. Unlike the traditional direct design method i.e. for determining the coordinates of other feature points, one or more fixed reference points are required as starting point which makes the designers job tedious to control remaining feature points. A fixed single reference point on reference surface of each sample field is considered. In iteration stage, the optimization is performed by improving the image quality without disturbing the shape and position of the freeform surface using an optimization algorithm through adjustments in coefficients of surface expression. Duerr and Thienpon [95] introduced a hybrid direct design method for imaging systems based on differential equations derived from Fermats principle and solving them using power series. The trial and error approach has been reduced to large extent to design optical systems that includes surfaces such as catoptric and/or dioptric spherical, aspheric, and advanced freeform elements. By this approach, a wide range of range of aberrations can be systematically balanced which provides deterministic solution rather than a global solution.

Method of confocal mirror design has the roots to the wave theory of aberration. Sasian extended the wave theory of axially symmetric system which requires immense understanding and usefulness of coordinate system [96]. The description of the imagery of an optical system is described with establishing a reference. In any plane symmetry system, such reference is defined as selected ray also known as optical axis ray (OAR). Its significance is same as the optical axis to description of the axially symmetric systems that provide the coordinate axis for referencing variables and also describe the whole system. In this approach of design, OAR and tilts are considered to define the optical surfaces. Further, aspheric and freeform surfaces were included in this approach of confocal mirror designs [97, 98].

Nikolov et al. [99] demonstrated the design-to-fabricate process for creating metasurface on freeform profile for the application of near-eye-display-inspired imager. This framework has significance in imaging and aberration correction using the metasurface phase response and the freeform optics shape. The principle of metaform states that the incident spatially and coherent light on the metasurface and freeform shape, interacts with the freeform surface, accumulating phase from optical path differences and additionally accumulating phase from the light–matter interaction with the nanoscale metasurface features. For reflective optics in an imaging system, the challenge of loss of light due to obscuration is overcome by the metasurface function to redirect the light in the preferred direction as of linear phase. Secondly, aberration correction such as astigmatism correction by freeform and balancing of aberrations is introduced by linear grating terms. Further, the coma correction is performed by the metasurface.

3.6. Performance-based optimization

Optimization is performed to improve the performance characteristic of the optical system while simultaneously providing a design that is manufacturable and preferably built at low cost. The coefficients for each component in a freeform optical system (i.e. Zernike, Forbes, splines and radial basis functions) are obtained by minimizing the merit functions using optimizing algorithms and it can be performed only when the boundary conditions and merit function are set. A few answers are needed to be provided during the optical design process: how far the object, image and the system is positioned? What should be the maximum size of the whole optical system?

Mathematical modelling of optical surfaces acts as the fundamental source for fast designing, optimization and true validation in terms of performance and efficiency. Genetic algorithm (GA) with the principle of biological evolution is widely used as numerical optimization method. During the design process of optics, environmental constraints such as temperature, electromagnetic shielding, humidity, etc are also considered in GA optimization. The nature of GA randomness allows people to find the global solution with crossover and mutations [100]. However, global optimization methods are not always feasible for the design of freeform optics as the solution space is large.

The multi-parameter optimization design techniques are the indirect design methods for generating optical freeform shapes. These methods are dependent on the analytic expressions that rely on a particular design parameter to be improved [83]. Designing a K-mirror system that consists of a freeform surface with the on-axis and off-axis conic element, a function like rotating a beam is provided to address an astronomical application. In the iteration process, design parameters for off-axis mirrors such as conic constant, aperture size, the radius of curvature, and off-axis distance are varied [101]. A typical example is to utilize freeform reflective-based optic LEDs to create a uniform and optimal illumination pattern within a circular far-field zone. To obtain a high optical performance illumination system, optimization is performed between controllable parameters such as zenith angle, LED to target plane distance, and distance between a specified point and the origin of coordinates. Outputs performance parameters such as small merit function with high efficiency and reduced relative standard deviation are obtained using the optimization technique based on control points of the freeform optics [102]. These design techniques are often very time-consuming because many iterations need to be performed to obtain the desired solution for design requirement. The initial design of
the surface has a significant impact on the performance parameters. Nowadays, these techniques are integrated into the packages of optical design software offered for commercial usage.

Commercial optical design software such as Code V and Zemax and their advanced features have made the designers to think out of the box and helped in the cost optimization of the whole optical products. CODE V has a local optimizer called Automatic Design and a global optimizer called Global Synthesis, which are both prominent optical design programmes. OpticStudio (Zemax OpticStudio) has a local optimizer (that can perform damped least squares or orthogonal descent algorithms for optimization) and two global optimizers such as Hammer Optimization and Global Search. As ray tracing includes a statistical component, it cannot accurately judge optical performance. At best, it can produce an approximation that improves with the addition of more rays.

4. Freeform optics machining techniques

Freeform optics can be manufactured by various method such as ultra-precision subtractive machining (turning, milling and fly-cutting) and ultra-precision grinding (UPG). The diamond tool life and achievable tool geometries significantly limit the application of ultra-precision machining in aspect of overall manufacturing cost. Grinding is well suited for the hard, brittle and optical materials but can have a high-cost manufacturing for complex structures. The following are the most recent subtractive manufacturing techniques for fabricating freeform optics.

4.1. Ultra-precision diamond turning

Surfaces with flat, aspheric, diffractive, and freeform profiles are straightforwardly generated using single point diamond turning (SPDT), also known as diamond turning machining (DTM). In the 1960s [103], the development of diamond turning technology and machine tools with Dupont was started. The beginning products fabricated using SPDT were the flat shape and basic cylindrical shape that fulfil the demands of electronics, computers, advanced technology for energy and defence applications [104]. The diamond tool edge may be sharpened to nanoscale precision, allowing for the removal of a thin layer of material and, as a result, the creation of high form accuracy and a smooth surface. The single point diamond tool tip exerts the cutting and normal force on the workpiece surface top layer with process parameters like feed and depth of cut. The material is removed in two regimes i.e. ductile mode [105] and brittle mode [106] depending upon the type of materials. Ultra-precision diamond turning is capable to provide optical quality for the ductile materials such as aluminium, gold, copper and its alloy, and acrylic plastics. With the systematic and proper implementation of tooling, selection of materials, machining approaches, processing algorithms, error compensation methods and cleanliness of the machine including the environmental factors, one can achieve the surface roughness as low as 1 nm and surface accuracy in order of 100 nm [107]. The general categorization of machine tools is based on various axes and their configurations. Figure 12 shows the multi-axis Moore Nanotech650FGV2 freeform generator. The flat and cylindrical shapes components can be fabricated using the two-axis (i.e. X axis and Z axis) lathe machine. Lathe machine with three-axis (X-, Z-, and C-axis) can deal to fabricate the curved shaped components where the third axis provides the indexing to the tool. Fourth axis (B-axis) adds the table rotatory axis which also reduces the vibrations during the machining as the tool tip points out perpendicular to the workpiece. The freeform rotational shaped components are generally fabricated using this configuration.

Slow tool servo (STS) is a simple machining technique that entails mounting a high accuracy encoder on C-axis to the spindle and this T-configuration contains two modulated axes movement at a constant speed while only the Z-axis oscillates (in several Hz) [108]. Linear Y-axis is adjusted before the machining operations and usually kept fixed.

In comparison to the other machining approaches, Davies et al discovered that STS performs better in terms of surface roughness and consumes more machining time. The reason behind the longest machining time is that the Z-axis is restricted with its motor speed and acceleration and it is huge in size as compared to the tool [109]. Numerous researchers have considered various parameters related to the tool [110, 111] such as nose tool radius, clearance angle, rake angle and tool design [112, 113] in generating the freeform optical surfaces.

Fast tool servo (FTS) is a system that has a set of micro-feed servo systems with fast and rapid response capability for ultra-precision machining tools. It was proposed in 1985 by Patterson and Magrab where a self-contained and independently servo-operated diamond tool holder was designed and built to increase the resolution and accuracy of a precision lathe [114]. The main categories for the actuation principles of FTS’s are hydraulic, magnetostriuctive, shear-stress electromagnet, normal-stress electromagnet, and Lorentz force (both rotary and linear). These devises are classified with respect to
strokes or their operating range such as long-stroke as above 1 mm, intermediate as between 100 μm and 1 mm, and short-stroke as less than 100 μm [115]. FTS is drastically used whenever there is requirement of diamond turn surface structures such as torics, micro lens arrays, micro prisms, off-axis aspherics with small sags (up to 10^2 μm), compound eye, sine grids, and Fresnel microstructures.

The machining time is more in processing of freeform optics and interaction between the diamond tool and workpiece. Recently, developments in laser-assisted diamond turning has found benefits in reducing the tool wear in ductile mode cutting of hard and brittle materials such as optical and IR grade materials and reducing the machining time. Micro laser assisted machining is proposed where the laser is passed through the diamond tool, allowing to increase the temperature of cutting zone that soften the material prior to cutting [116].

Usage of high-frequency response motions and additional axes makes this technology to produce high quality of freeform optics with high level of precision. Disadvantages in ultra-precision diamond turning are the diamond tool’s life, high energy demands and high maintenance cost.

4.2. Ultra-precision milling (UPM)

UPM is a high-speed machining process where the tooltip is of diamond and the cutting tool is fixed on and rotated with the spindle. This machining technique is used to create microstructures [117] and channels [118] for various applications such as biomedical, imaging and lighting. The surface quality of freeform surfaces is dependent on the critical process factors such as spindle rotational motion errors, vibrations caused by motion drives, feed rate, spindle speed, geometry of the tool and material factors i.e. swelling, crystallographic orientation and material anisotropy. UPM of freeform in figure 13, visualizes the milling arrangement, tool geometry i.e. zero rake, 1.5 mm tool tip of single crystal diamond mill and milling geometry with zero inclination angle between the workpiece normal and milling tool axis, uncut chip thickness (t_c) and dA. Cheng et al [119] performed the raster UPM on the Aluminium alloy (AL6061) and Copper alloy. The results showed the feed rate effects on the surface roughness i.e. arithmetic roughness increases with increased feed rate during horizontal cutting and R_a increases with the decrease in feed rate during vertical cutting. Li and Yi reported the work related to the high-speed micro milling and fabricated micro aperture on the complementary metal-oxide semiconductor sensor with freeform micro lens array and the relay optics [120]. Figure 14 visualizes the spherical concave artifacts and convex freeform surface using the three-axis ultra-precision machining. These artifacts are obtained on the brass with cutting parameters i.e. spindle speed of 44000 rpm, zero inclination angle, feed per tooth in Y-direction were 9 μm for rough cutting and 1.4 μm for finish cutting, depth of cut 300 μm and 50 μm.

One cutting edge on same tool holder limits the efficiency of UPM and operation of feed axes and spindle at high speed requires precise control techniques. These factors may raise problems for the freeform optics fabrication. A new mechatronic device is introduced along with the automated micro-fluidic balancer [121]. Low surface quality in brittle materials, burr formation, workpiece material deformation, are some disadvantages of UPM.

4.3. Ultra-precision fly-cutting (UPFC)

UPFC is an intermittent cutting procedure that uses a diamond tool positioned on a spindle to remove material from a workpiece. The tools feed onto the workpiece is applied in a perpendicular direction, resulting in achieving various feature based freeform surfaces. The fly-cutting process can be performed in two ways i.e. end-fly-cutting (EFC), and radial-fly cutting (RFC) [124]. EFC is a standard practise for obtaining large freeform smooth surfaces with excellent surface quality and the tool is fixed parallel to the spindle axis. The tool is kept along the radial direction of spindle in RFC and this technique
is capable to generate the special features. When these two techniques are combined with the FTS and STS machining approach, freeform surfaces, the micro channels, diffractive gratings, prism arrays, and other hierarchical surface features can be generated. The experimental setup of UPFC is shown in figure 15 where the workpiece is mounted on the angular table (b-axis) of the five-axis UPM machine (Precitech Freeform 705G). The tool is held stationary on the high-speed spindle by a predetermined swing radius. Maximum distance between the tip of the tool and centre line of the rotational spindle is defined as Swing radius. For the fabrication of freeform optics, the feed to the tool is provided in the horizontal x-axis and the tool performs intermittent cutting on the surface of the workpiece. The workpiece moves in translation along the z-axis similar to the STS for the generations of deterministic primary shape. The tool’s raster motion along the y-axis removes the required amount of material from the workpiece surface. These steps are repeated in designed cycle until the required freeform surface is obtained. UPFC principle stands unique in terms of ductile machining mechanism different from other ultra-precision machining techniques [125]. Very small chip thickness of 80 nm was obtained using the large swing radius of 40 mm in producing the F-theta lens of single crystal silicon. UPFC is a time taking process when compared with the diamond turning, therefore it is highly recommended to increase the feed rate in first cut in order to reduce the overall machining time. Surface roughness achieved during the first cut is higher but shape obtained is practically undisturbed for freeform surfaces. However, this effect can be minimized by correction loops i.e. fast rough cuts which also facilitates the reduction of form errors. Finish cuts are used here to smooth off the freeform surface without changing its shape. Special freeform designs such as rectangular biconics and components for head-up displays are more suitable to be manufactured using the UPFC technology [126]. Also, the freeform optics such as hyperbolic paraboloid is fabricated using fly-cutting with the nose tool radius of 3 mm, clearance angle of 6°, depth of cut 5 µm, and rake angle of 0° [127]. As this fabrication process provide intermittent cutting, the cutting efficiency achieved may be poor, hence special functional surfaces are appropriate to be manufactured using this technique.

4.4. Ultra-precision grinding (UPG)

UPG is the abrasive-based material removal technique that uses the grinding wheel with ultrafine grains. Brinksmeier et al [129] described the UPG processes with achievable outputs such as a root-mean-squares figure accuracy < λ/10 with λ < 1 µm, Sa < λ/100 as surface roughness, and damage free sub-surface to prevent light scattering in transparent optics and avoid crack formation in the workpiece. UPG experimental setup consists of a confocal probe measurement, workpiece held on workpiece spindle using fixture, and the
grinding diamond wheel mounted on tool spindle that is kept perpendicular to the workpiece as shown in figure 16. UPG is well suited for the processing of hard and brittle materials, such as ceramics, silicon carbide, fused silica, glass etc. The grinding trace left over the grinded surface are fine with very small surface height [130]. The abrasives perform the multi-cutting actions to generate high surface integrity at reduced tool wear as compared to the diamond cutting. While, performing UPG on hard and brittle materials, the challenge arises due to their mechanical properties. The transition from brittle-to-ductile behaviour in material removal via chip deformation has great significance in the UPG and depends on the stresses involved during grinding cycle. Ductile mode machining regime for optical materials requires a maximum chip thickness not beyond the initiation critical value of crack. The critical chip thickness in particular grinding process with respect to material properties [131] are estimated using the equation (6),

\[ dc = 0.15 \left( \frac{E}{H} \right) \left( \frac{Kc}{H} \right) \]

where \( E \) is Young’s modulus, \( Kc \) is fracture toughness, and \( H \) is hardness. Other crucial factors are the temperature, strain rate, stresses i.e. tensile and axial.

The key issue when grinding freeform and curved surfaces is to maintain the workpiece’s form accuracy throughout the process by using a precise grinding tool. Various grinding kinematics have been developed such as cross-grinding, parallel and fixed spot grinding based upon the contacts between the grinding tool and workpiece for different surfaces are shown in figure 17. In cross-grinding, the material is removed by keeping the tools cutting directions perpendicular to the workpiece rotational axis. Wear of the grinding tool is mainly focused on the contact point which is a problematic condition to maintain a required form accuracy for large size optics. Whereas in parallel grinding, the grinding tool is kept at 45° tilted to the vertical held workpiece. Here, the form accuracy obtained is better than the cross-grinding as the contact area between the grinding tool and the workpiece is spread widely. Chen et al [132] worked with grinding in cross mode and parallel mode on aspherical monocrystal silicon. The contact area is more in the parallel mode between tool and the workpiece. This can be useful in terms of simplified dressing of the grinding tool after the grinding cycles. With the addition of \( Y \)-axis, the grinding tool maintains the normal degree angle with respect to the workpiece and the grinding spot is uniformly kept fixed. The grinding wheel must be redressed so that the abrasive particles keep protruding from the surface of the grinding tool. Due to the included ultrasonic vibrations along wheel-axis direction, the self-redressing of the grinding tool occurs which makes this process more suitable for grinding large optics. Freeform surfaces generated using UPM with radial in-feed provides solution for the figure corrections. The fixed spot UPG point-contact is utilized to produce aspherics and freeform surfaces, while the area and line contacts are employed for mass production of flat and spherical geometries using cup and pellet wheels. Figure 18 shows the two off-centre biconic freeform optics with different optical specifications produced by the UPG. The grinding was performed in stages such as rough grinding at spindle speed 6000 rpm, grinding depth 10 \( \mu m \), and fine grinding at 6009 rpm of spindle speed and 0.5 \( \mu m \) of grinding depth. In a 220 mm \( \times \) 105 mm measurement area, the PV-values of the machined surface with profile error compensation decreased from 21.6 \( \mu m \) to 1.5486 \( \mu m \) [133].

The manufacturing techniques used for the products with freeform optical surface are listed in table 2. Clamping techniques, which allow different types and sizes of workpieces to be held with the needed force during ultra-precision cutting, are also a hurdle in the fabrication of freeform optics. The balancing and alignment of the workpiece on the fixtures in subtractive manufacturing methods, adds to the complexity of the production process cycle. Also, what material cutting approach should be used to make optics with large sag and curvature differences? is still unanswered.

5. Finishing processes

To convert the optical ground workpiece into a final optics product, it takes several fabrication processes, such as the grinding, machining, and polishing. However, every machining process leaves out tool footprints, unexpected patterns and speckles on the generated complex freeform surfaces. Therefore, the surface defects and sub-surface damages (SSDs) remained after performing each operation on the optics need to be removed to achieved optimum performance optical components. The surface and sub-surface defects can only be removed the superfinishing processes. On optical materials the topography errors such as low-spatial frequency, mid-spatial frequency, and high-spatial frequency are controlled using several polishing corrective techniques. The reference of ISO 10110-8:2019 can be used to distinguish these errors [158]. Following are the widely implemented figure correction techniques for the fabrication of freeform optics.
5.1 Bonnet polishing

The bonnet polishing is a sub-aperture deterministic polishing technique where the tool size is smaller than the workpiece. In 2000, this polishing technique was proposed by Zeeko and Walker. According to the research, the material removal rate may be regulated between 0.025 and 120 mm³ min⁻¹ [159]. A spherical bag made of knitted cloth and rubber lamination serves as the bonnet polishing tool. The polishing film on the surface of tool gets inflated by the compressed air and it provides stability to the shape. The spindle speed and airbag pressure inflation are two major elements that influence the performance parameter, i.e. surface roughness. Figure 19 illustrates the schematic diagram and actual machine tool of the bonnet polishing. The polishing tool can be rotated in B-axis and A-axis along with rotatory movement of polishing head and the workpiece is provided with the X-, Y-, Z-axis along with the table rotation.

Kinematics of the grinding head in the bonnet polishing are of various types [160]. Different types of grinding head tilts with the polishing tool are as follows:

- Rotation tool (Airbag) axis is perpendicular to the workpiece. It provides the polishing trace in circular pattern. The processing convergence is dull, and this approach is applied at the pre-polishing stage.
- Rotational axis of the tool is tilted between 15° and 20° from the normal of the workpiece. It generates the polishing trace in the eccentric form. This approach is used for the precision polishing as the process convergence is strong.
- There are two rotational axes such as, one rotational axis of the tool is perpendicular to the workpiece and second, the...
### Table 2. Manufacturing techniques for the freeform optics and their applications.

| Application with freeform element | Process/Method | Products |
|-----------------------------------|----------------|----------|
| Car head lamp                     | DTM-STS + DM [136] | LED      |
|                                   | DTM [137]       | Aspheric mirror |
| Big-screen high-resolution television projection system | DTM + Diamond Micro-Milling [138] | Refractive infrared lens array |
|                                  | Diamond Micro-Milling + Fly Cutting [139] | Freeform imaging element |
| Beam shaping and computational imaging | DTM-STS + Microinjection Moulding [140] | Freeform micro-lens array |
| Beam shaping                      | DTM-STS + Moulding + Thermal Slumping [141] | Freeform primary mirrors |
| High concentration photovoltaic system | DTM + Moulding + Thermal Slumping [141] | Freeform primary mirrors |
| Reflective beam shaping            | Diamond Micro-Milling [142] | Biconic lens |
| Illumination—road lighting engine  | CNC Turning + CNC Milling + Compression Moulding [143] | LED |
| Fresnel concentrator               | SPDT + Fly Cutting [144] | RX Fresnel lens |
| Infrared imaging system            | DTM-FTS [145] | Near-rotational freeform surface |
| Light transmission                 | DTM_STS [146, 147] | Sinusoidal grid and micro-lens array |
| Augmented reality and head mounted display | DTM [148, 149] | Freeform lens |
| Precision moulding                 | STS Grinding + Glass Moulding [150] | Toric Tungsten carbide mould for concave freeform optical surface |
| Bionic and optical applications    | DTM-(STS + FTS) [151] | Compound freeform surfaces |
| Multifocal lens for eye-vision     | DTM-STS [152–154] | Progressive addition lens (PAL) |
|                                   | DTM-FTS [152, 155–157] | |

Figure 19. Bonnet polishing tool (a) schematic diagram and (b) IRP 600 polishing machine. Reprinted from [19] © 2019 Optical Society of America under the terms of the OSA Open Access Publishing Agreement.

Polishing with a bonnet tool may eliminate a 10 µm defective layer off the surface of a 1 m hexagonal workpiece in 167 min [161]. This sub-aperture polishing method can polish quickly while removing a large amount of material [162]. The bonnet polishing is more suitable for the large aperture optics and finds optimal implementation for small size components.

#### 5.2. Magnetorheological (MR) finishing

The MR fluid behaves as Newtonian fluid in the absence of magnetic field. The MR polishing fluid stiffens when the external magnetic field is applied. Figure 20 explains the MR behaviour of the MR polishing fluid in the magnetic field on...
and off conditions. Magnetizable iron particle aligns under the influence of magnetic field and traps the abrasive particle between their chains. Therefore, the fluid viscosity can be changed with the change in the magnetic field. The MRP fluid is represented by the Bingham plastic model \[ \tau = \tau_0 + \gamma \eta \] as given in equation (7),

\[
\tau = \tau_0 + \gamma \eta
\]

where \( \tau \) is the shear stress of the fluid, \( \tau_0 \) is the magnetic field induced shear stress, \( \eta \) is the dynamic viscosity of the MR fluid, and \( \gamma \) is the shear strain rate.

In 2004, Gorana et al reported that the finishing process itself consumes 15% of the overall manufacturing cost [164]. Hence, several researchers have contributed to the finishing of various shapes, forms, and different materials to work on the assets of accuracy and quality of the surfaces. The challenges in obtaining a mirror-like surface and defect free optical components includes heat generation during the rubbing process, traditional finishing processes produce the surface damages and sometimes could not able to remove the SSDs, and there is no control over the forces. Therefore, to overcome these difficult problems along with control over indentation and cutting forces, the MR finishing was developed for figure correction of various materials with different shapes [165]. MR finishing setup developed for finishing of flat, curved, and freeform optics consists of a polishing tool with magnets (either permanent or electromagnets), MR polishing fluid delivery system, servo motors and mechanical precision drives. MR finishing is used to precisely finish the optical components and obtain a defect free surface with the surface roughness in nano-level range [166]. MR polishing fluid consists of magnetic iron particles, abrasives, and fluid medium [167]. Deionized water is used as a carrier medium for the finishing of the optical glass. The MR finishing technique employed to reduce the surface roughness of BK7 glass specimen includes a solid core tool, electromagnet, mechanical precision drives and indigenous MR polishing fluid. The surface roughness achieved was 17 nm from 41 nm in 90 min of finishing cycle with parameters such as 300 rpm of core tool rotation speed, 1 Amp of current, and 0.8 mm working gap between the tool and workpiece surface. Results showed significant improvements in the optical performance such as transmission, and reflection of the optical components by MR nanofinishing. Nowadays, different types of MR finishing setups are developed depending upon the type of freeform surfaces to be finished and toolpaths such as raster, spiral, etc. Finishing with spiral toolpath can provide corrections in freeform rotationally symmetric features and tighter edge exclusion [168]. Research scope lies in the development of the nano-size magnetizable abrasives particles with novel structures (cutting edges) which can further reduce the finishing time and surface roughness of the optical surfaces without SSDs.

5.3. Laser polishing

Laser polishing is a non-contact type thermodynamic process that uses a laser as energy source to irradiate the workpiece surface, reduce the surface roughness and minimize or eliminate the defects [169]. The experimental setup of laser polishing is shown in figure 21(a) that consists of a laser source, high speed camera, laser protection filter, process chamber, oxygen measuring device, and a pyrometer for high temperature monitoring. The laser irradiates the surface causing free electrons to vibrate and further emit the wave that undergo mild projection and high reflection. According to the changes on the workpiece surface the laser polishing are categorized in two types such as cold polishing and thermal polishing. The cold polishing includes the local laser ablation and large area laser polishing [170]. The chemical bond between the molecules breaks when molecules absorb high photon energy at time of laser irradiation. In laser polishing technique, the vaporization of molecules occurs from the high to low polymer molecule and low surface roughness is achieved [171]. There should not be any type of heat accumulation forms on the workpiece surface. Therefore, it is recommended that short pulse with short wavelength is best suited for cold polishing. In thermal polishing, the workpiece surface under goes the re-melting or evaporated due to the heat accumulation and directly reduce the surface roughness [172]. The workpiece is smoothened by the melting process and material distribution in the working area of laser. Pre-heated workpiece is allowed to pass

![Figure 20. Magnetorheological (MR) effect, left image shows the MR polishing fluid without magnetic field and right image shows MR polishing fluid with magnetic field.](image-url)
under the high-power density laser that melts the materials, followed by the measurement of surface. These measurements are performed in on-line mode to evaluate the form errors and scanned script is prepared by the measured data points. The complete laser-based process route to fabricate the optics is shown in figure 21(b). This technique is capable to polish the complex surfaces (i.e. freeform and intricate surfaces) that are not polished with traditional manufacturing techniques [173].

The surface characteristic can be altered by the controllable parameters such as angle of incidence of the laser beam, pulse duration, type of laser, processing temperature, power, beam wavelength, scan speed and number of the passes. Weingarten et al conducted the laser polishing and laser beam figuring on the mechanically polished optical glasses such as BK7, fused silica, and S-TIH6 to correct the shape, waviness, and surface roughness [174]. To avoid the cracks, pre-heating temperature for BK7 and S-TIH6 was 600 °C as these glass materials have low thermal shock resistance. The waviness on fused silica was controlled to >100 μm laterally and <50 nm vertically. Hecht et al performed the CO₂ laser beam polishing on fused silica with reduced surface roughness within range to 5 < Rₐ < 15 nm from 200 < Rₐ < 800 nm. The processing temperature was maintained between 1900 °C and 2100 °C to prevent from the sublimation of material under laser scans with wavelength of 10.6 μm [175].

The challenges of laser polishing are also limited to the precise scans over the workpiece, pre-heating that could increase the energy consumption, locally heat-affected zone, and not suitable for reflective materials.

5.4. Ion beam polishing (IBP)

IBP uses the plasma to remove atomic level material in a controlled manner. This technology is capable to provide nanoscale figure correction by employing a mode called location specific processing (LSP). In LSP, the material is removed layer by layer or non-uniformly from the surface to correct form error or surface uniformity errors of the component [177]. Ion source emits the ion beam with optimized spatial distribution along a certain energy which impacts the top surface of the workpiece up to a well defined depth. The direction of the ions, flux between the working gap, and energy may be individually controlled [178]. Therefore, the energy absorbed plays a vital role in material removal i.e. if the absorbed energy is greater than the lattice binding energy, a disturbance is created between the workpiece atoms as the atoms displace from their equilibrium positions and may results in collision with the near around atoms to propagate the action. The atoms present in the workpiece receives the energy transferred from the collided ions at the top surface as shown in figure 22. If the energy level absorbed is insufficient by the workpiece atoms to overcome the lattice binding energy, then the absorbed energy is released in the form of phonons [179].

Between the ion source and the workpiece surface, there is no direct mechanical contact. The working gap is kept small to reduce misalignment between the ion source and the workpiece’s polishing spot. As a result, polishing can be done in a specified location without affecting the surrounding region. In IBP, the material removal function is like the Gaussian spatial
distribution that results in stabled and controlled removal [181]. IBP is dependent on the environmental conditions i.e. requires vacuum to establish the ion beam that may affects the efficiency of the polishing system. Chkhalo et al. worked on the problem of surface roughness metrology and polishing of diffraction-quality x-rays mirrors of fused silica and optical ceramics for spectral range below 10 nm [182]. The research focused to understand the stability of these materials under IBP and the conditions optimal energy requirement to smooth the surface. The depth of material removal during IBP over a large range of spots were considered because if the LSP removes surface errors in nanometric range, this could reach to micrometres during the aspherization of the surface. Therefore, etching was carried at near normal incidence angle with the constant rate to obtain LSP. IBP with Neon and Argon ions at energy level of 1000 eV resulted in reduced surface roughness from 0.44 to 0.33 nm for fused silica and for Zerodur was 0.42 nm with energy level 300 eV and 800 eV. Time consumption is a limitation with this process as the polishing is done at very small spot. Bauer et al. carried out IBP of aluminium alloys with oxygen or nitrogen gas for short wavelength [183]. The etching depth was achieved up to 400 nm and 1 µm without disturbing the initial surface topography of the specimen. The surfaces get degraded by the formation of the etch pits if the etching depth is beyond these limits. Also, the most suitable narrow beam tools with 0.6 mm to millimetres in width found to perform appropriate figure error correction without increasing the surface roughness. The limitations of IBP method are its environmental dependence, and it is not suitable for the metals as they can reflects back the energy beam that can results in radiation and damage to near operator or environment.

6. Techniques for mass production

Huge quantity of freeform optical components are required to be manufactured to overcome the high demands of industries, research and development centres, hospitals etc. Production of freeform optics should be non-negotiable with high production efficiency, form accuracy, low surface roughness, minimal SSDs and textures. Combining all the technicalities and needs, complex shapes with large production have become the most challenging task in optical fabrication industry. Following are the formative manufacturing processes used for the mass production of freeform optics.

6.1. Injection moulding

Injection moulding is a cost-efficient method for reproducing optics for prototyping, and user end-products. It is a short cyclic process with a simple mechanism. Because the enormous volume divides the initial cost, the original investments become almost insignificant at the end of production cycle. The fabrication process route follows several steps, from the development of moulding die via machining processes, selection of materials to the final consumer usable optics such as mobile cameras, gaming devices, CD/DVD players, contact lenses, etc [184]. Initially, the moulding dies are designed for optics of required size and shape such as flat, curved, symmetrical and non-symmetrical, along with roughness requirements and surface quality. First step is to feed the plastic pellets into the hopper that pass to the plasticizing screw. The pellets are mixed and converted into molten state by external heating element. Screw facilitates the movement of molten plastic by the rotational motion to shift it into the mould cavity with high pressure via injecting nozzle. The injected molten material is further mechanically pressure. Then the material is left to cool down (i.e. solidification stage). The delivery system stops the flow of molten material into the moulds as the entire cavity is occupied. The pressure is released with the opening of the dies through the retraction of punching die, temperature gets normalized, and the product is ejected from it. Again, the mould is closed for next cycle of production [185, 186]. The injection moulding process including the components of machine is illustrated in figure 23.

To control the performance parameters of injection moulding, such as form accuracy, surface roughness, and residual stresses, the values of process parameters such as injection velocity, mould temperature, cooling time, dwell pressure, and melt temperature are varied. Dick et al. demonstrated a process chain for mass production of high precision freeform optics [187]. The Zernike freeform optic was obtained at the stabilized process parameter condition i.e. 240 °C melt temperature, dwell pressure of 1000 bar and 90 °C of mould temperature within a clear aperture of 40 mm, and form shape deviations were successfully minimized to 0.24 µm p-v at the mould and about 2 µm at the moulded freeform surface. Using the hybrid artificial neural networks and particle swarm optimization techniques, the prediction was made for the optimum injection moulding process conditions of bi-aspheiric lens. The material used was polycarbonate for the bi-aspheiric lens as shown in figure 23(b) [188]. The experimental estimation was 6.93 mm of the magnification of the lens and FOV of 71.6° respectively. Li et al. [189] performed the micro-injection moulding process to fabricate the Alvarez lens with polymethylmethacrylate (PMMA) and Plexiglas V825. The mould inserts of Nickel alloy were fabricated using the ultra-precision machining with surface roughness Ra of 6 nm. The molten temperature of the materials was kept at 250 °C, mould temperature of 35 °C, injection velocity of 220 mm s⁻¹, maximum injection pressure of 150 MPa, packing time of 3 s, and cooling time of 50 s. Zhang et al. [190] performed parametric study on the variotherm-assisted micro-injection moulding that manufactured micro lens array for light-field applications. Mould
temperature, melt temperature, and packing pressure were the variables studied for preliminary trials in this study. Critical issues of demoulding were observed at 60 °C mould temperature, 225 °C of melt temperature, and packing pressure 135 °C, hence, to achieve geometric accuracy and surface quality the packing pressure was reduced to 75 °C.

The disadvantages of injection moulding are high tooling cost at initial stage of production, long set-up time of machine and moulds, and running cost which is often very high for small runs.

6.2. Glass moulding

Precision glass moulding, also known as the replication process, is a thermal expansion and moulding process that converts a glass blank into a precision functional optical component. This approach is ideal for high-volume optics production. Direct machining methods for optics production require pre-grinding and post-polishing phases to achieve the application usable level, which makes the optics high-priced. The glass material preform (i.e. glass blank, ball, gob, disc, etc) is inserted into the mould after it has been pre-heated. The moulding chamber is then evacuated with an inert gas such as nitrogen or oxygen and the heating process begins. When the temperature is raised over the glass transition temperature ($T_g$) and the glass achieves a certain viscosity range of $10^9$ dPas (approx.), the heated glass material is moulded using a mechanical press to achieve the desired shape and finish. Compression force is applied in a controlled way and the temperature is kept constant for a specific period. The mechanical pressed glass element takes the shape of mould cavity and allowed to cool with continuously applied compressive load until the glass temperature drops below the strain point of glass. Once this condition is reached, the optical element is demoulded by removing the load, rapidly cooling it and safely ejected from the mould, as shown in figure 24(a). To avoid damage to the fabricated surface of optics, such as scratches and roughness errors, proper safety handling procedures must be followed. When compared to the machining techniques used to fabricate the final optics, this process takes less time. However, ultra-precision machining is also included in this glass moulding process route in terms of mould fabrication and post-machining for mould maintenance that occurs after performing numerous mechanical pressing operation [192]. Repeated heat fluctuations and mechanical loads can induce changes in the shape of the mould, resulting in inaccuracies on the surface of the mould. Material having satisfactory mechanical and thermal properties, such as tungsten carbide, is recommended for these reasons. Coating is also preferred to increase the life of moulds. Nickle-phosphorus coatings, for example, have a high hardness (HRC in the 50–55 range) and can withstand temperatures up to 1400 °C. The glass moulding process needs to be performed in controlled environment [193] including thermal and mechanical loading–unloading.

Rotational freeform structured optics of Schott P-SK57 was fabricated using the micro machined silicon mould and further coated with graphene-like-carbon to avoid the sticking between the mould and glass [194]. The lenslet was $360 \times 360 \ \mu m$ in size, with a radius of curvature of 7.1119 mm and an effective focal length of 12.1157 mm. Because of chemical vapour deposition covalent-bonded graphene-like-networking, the results revealed superior glass moulding because there was no sign of adhesion between working zones. The mould insert for fabricating the concave freeform surfaces of high accuracy was grounded by UPG with STS. Freeform optics obtained after the glass moulding using the grounded toric tungsten mould had the mirror like surface as shown in figures 24(b) and (c) [150]. Surface roughness of both the grounded and moulded surface was obtained $S_a$ and $S_q$ approximately 5 nm and form deviation under $PV = 530 \ \text{nm}$ for
6.3. Coating

The last step in fabrication of freeform optics is a thin-film of protective and light-controlling coating. There are various types of coating depending upon the performance characteristic of the optics such as antireflection [198], metallic reflectors [199], high-efficiency dielectric reflection and multiple-layer filters [200]. Coatings on optical components are commonly used to ensure long-term durability and high performance by stacking layers of materials to obtain tailored optical properties. Some optical coating methods [201] are atomic layer deposition, chemical vapour deposition, sputtering, ion plating, ion-assisted deposition and sol–gel. Many optics applications benefit from coating. For example, to minimize ghost images and enhance transmission, the objective optical component for photographic and video requires three layers of thin-film coating. Multi-layer coatings are applied on the windows, prisms, and beam splitters to focus the spectral regions improved optical characteristics. Large-area coatings are used in the strategic application to increase the contrast of military cockpit instruments. Industrial laser systems totally rely on the protective coatings to provide survivable surfaces for high energy work. Table 3 lists out the type of coating methods and their applications. Coating on steep angled freeform optics with atomic layer deposition method is performed that enables very uniform coatings over any shape [202]. In atomic layer deposition coating, for low refractive index material SiO₂ and Al₂O₃ and for high refractive index materials ZnS, TiO₂, ZrO₂, HfO₂, etc are preferred. Dome profile have been anti-reflective coated with five layers of TiO₂, SiO₂ and Al₂O₃ films by atomic layer deposition [203]. The reflectance is reduced from 8% to below 1.2% at visible spectral range i.e. 420–670 nm by applying double sided anti-reflective coating.

7. Metrology

The most supportive technology for the ultra-precision manufacturing is metrology. In this section, we have conducted the review of various metrology techniques for measuring the form and finish of the freeform optics. The ultra-precision machining techniques provide high accuracy in producing modern complexed optics after being impacted by various factors such as tool wears, vibrations and machine tool system errors, environmental errors, and profile errors. Profilometric, interferometric and non-interferometric techniques are considered as the typical surface metrology methods for precision optical components. Both the commercialized and research laboratories capabilities-based measuring approaches are summarized. These techniques are categorized based upon
the type of contacts i.e. contact between the measuring probe and the workpiece surface.

7.1. Contact based metrology

Every ultra-precision machining process have certain processing range which must be considered in order to achieve high precision optics. The faults and the damages introduced during and after the fabrication process due to existing machine tool provides an estimate of the manufacturing capabilities, cost and time related to overcome those defects through compensation. The contact type measurement has the long history in the measuring the optical surfaces. Further, based on measured data, the quality is defined. A coordinate measuring machine (CMM) is a device that uses a probe to sense discrete points on the surface of a physical object to determine its geometry. CMMs are widely used to measure the conventional and non-conventional optics by employing the Abbe’s principle. The point contact-based measurements allow to quantify large steep surfaces over large area measurements. The rotational symmetrical lenses are scanned and measured using the tactile 2.5D probes with diamond tip of conical and pyramidal shape [204]. The 2.5D probes principle and standard can be found in ISO 3274:1998 [205]. Measurements of surface finish, waviness, form of the 3D optical surfaces can be performed using the Taylor Hobson Form Talysurf® PGI Freeform [206]. The sensitive stylus is allowed to make physical contact with the surface of optical component, draw scans over the required range. The variations and surface deformations of the surface are registered with the stylus displacement as a function of position. Profilometric instrument is capable to work for many freeform optics such as NURBS, Zernike, toric, bi-conic, ellipsoid, etc. This instrument is functional for slopes up to 50° and resolution down to 0.8 nm. Contact-type radial form measurement technique is proposed to reduce the measurement errors [207]. An aluminium alloy mould of large curvature freeform surface is measured using Form Taylorsurf PGI 1250A profilometer with stylus of 400 µm radius ball tip of part number 112-3450, as shown in figure 25. Workpiece of 24 mm curvature radius and 30 mm diameter is fixed on rotary stage and gentle slope in longitudinal direction is provided by the tilt stage. The freeform small features are measured using the microtactile 3D probe named ‘Triskelion’ of National Physical Laboratory and IBS Precision Engineering [208]. The probe tip diameter of 70 µm enables the measurement of small features i.e. inside diameter of small holes up to 1 mm depth. Some challenges that impact the development process route of freeform optics are long time of measurement, state errors, and normal contact conditions of the probes with the surface. These conditions require additional tilt axes or highly adaptive CMMs for various coordinate systems.

Cylindrical CMMs with optical and tactile probe utilizes the fiducials as reference coordinates system for the measurement of freeform optics [209]. The shape deviation of freeform optics is measured using UA3P-5 tactile 3D profilometer. The atomic force probes with laser-based positioning of axes achieved uncertainty of 100 nm and repeatability of 50 nm for the slope up to 50° [210].

The advantages of the contact type metrology techniques are the traceability of long-distance measurements and exact wave profile. However, a few disadvantages are also associated with these techniques such as wear of stylus, inability to measure viscous samples, requirement of sample cutting and for tracing by the detector, measuring pressure may induce scratches on the surface of the optical components, measuring probe tip radius restricted measurements, and difficulties in exact location profile measurement on a freeform optics.

7.2. Non-contact freeform metrology

Non-contact measurement of freeform optics is possible with interferometric techniques where the entire surface is measured at once. Interferometry can be performed very fast with precision as compared to the contact type metrology. Environmental factors such as moisture, temperature, etc may affects the accuracy of the measurements and chips remained after machining, lubricant, dust, coating on the samples also influences the measurements [23]. Interferometry is method of measurement which utilize the phenomenon of interference of light wave, sound waves or radio waves. Optical interferometry has been used for more than a hundred year and its accuracy is improved using the lasers. Laser Fizeau interferometers has proven in surface measurement of flat and spherical shapes in terms of form and mid-spatial frequency [211]. For arbitrary shapes the challenges arise with deviations in departures from mild to extreme, the reference wavefront may produce reference pattern which is hard to be resolved by interferometers camera. The optical null lens or computer generated hologram plays an important role in producing reference wavefronts [212]. However, they are not feasible for every type of freeform surfaces. Therefore, specific design and proper fabrication of such optical diffractive element maintains the accuracy of the measurement system. Challenges are found in alignment of computer-generated holograms and wavefront magnification matching of samples. There is an increase in fringes of the detector with the mismatch of reference and

Figure 25. Stylus profilometry of large curvature freeform surface. Reproduced from [207] © 2019 IOP Publishing Ltd.
sample. The solution for this is to reduce the aperture size or imaging the surface in small segments and further mathematically stitching of the large measurement area [213]. Surface measurement of freeform optics is conducted by the researchers by utilizing various interferometers such as lateral shearing interferometer [214] and tilt wave interferometer [215]. Interferometry technology finds applications in optics shape measurement [214], radio astronomy [216] and space [217], and many more. A surface measurement technique with active control over environmental noise which utilized wavelength scanning interferometry was introduced [218]. This approach provided solutions to problems such as thermal drift, air turbulence, and mechanical vibration which can cause invalid results and errors in surface measurement. The advantages of interferometry over other surface measurement techniques are its extremely sensitiveness to surface topography, which is normally measured in nanometres and does not require mechanical contact with test sample. However, the interferometry limits by the type of software and test sample used.

Phase measuring deflectometry (PMD) is a reliable and cost-effective 3D optical metrology technique based on 2D fringe phase measurement [219]. The basic principle of PMD is based on the law of reflection [220]. For PMD, it states that the reflected ray will have a double angle (2α) if the test sample angle (α) is changed in relation to a reference orientation. In PMD, the probe rays are projected on the test surface and irregularity of surface produce variations in the fringes. The shape, profile, and curvature of the surface is obtained by phase-shifting fringes. PMD finds application in precision manufacturing, reverse engineering, quality control, and many more. The challenges lie in complex surface measurement due to the size of screen and the test sample, and measuring time. A modal PMD was proposed for mono-PMD, stereo-PMD, and multi-camera PMD configurations [221]. With the mathematical models such as Zernike polynomials, Chebyshev polynomial or B-splines, this method presented the simultaneously estimate of slope and height of surface under test. PMD experimental system consisting of one test sample, two cameras and one liquid crystal display (LCD) screen setup is shown in figure 26. Two Manta G-145 CCD cameras and Dell P2414H LCD, and a concave mirror of 95.3 mm wide and 200 mm long as test sample forms the stereoscopic configuration, a portable slope measuring deflectometry system was developed to measure slope with high accuracy [222]. This portable system was to perform measurements of 25 mm diameter mirror on 10 mm diameter micro display and found capable to achieve mid to high spatial frequency metrology. Large misalignments in telescope applications limits the interferometric tracking. PMD was used to determine the 5 degrees of freedom of misalignment in telescope segmented mirrors [223]. PMD has distinct advantages such as full-field, automatic data-processing, high precision, large dynamic range [224, 225].

The depth of the SSD in grinding process of optical workpiece requires specific study which cannot be obtained using the contact type surface measuring. Optical coherent tomoscopy, and laser scattering are among widely used measuring techniques for SSD [226]. Surface scattering techniques analyse scattered light from surface topography (including roughness), contamination, bulk index variations, and SSD to provide a solution to surface characterization [227]. Total internal reflection microscopy (TIRM) has been applied to detect surface damages and SSD in optical materials by the researchers [228, 229]. The working principle is explained as a sample is placed on a prism along with a layer of the corresponding fluid sandwiched between them. The sample is irradiated by the linearly polarized light allowed through the prism and fluid. If the sample is in good condition, the entire reflection occurs at the sample-air interface. Otherwise, the damage within the sample scatters the incident light. A fraction of the scattered light passes through the sample, allowing for microscope views of the damage. The sample must have a low surface roughness and be transparent to incident light for TIRM to work [230].

Figure 26. PMD experimental setup consisting of two CCD cameras, one test sample and one liquid crystal display. Reprinted with permission from [221] © Optica Publishing Group.
7.3. On-machine surface measurement (OMSM)

A suitable probing system is incorporated into an ultra-precision manufacturing machine which is known as OMSM. The movement of measurement system is performed by the regular drives of the machine. The linear variable differential touch probe is usually installed on a commercial diamond turning machine for fast alignment. Most recently, to improve freeform machining efficiency, OMSM and error compensation-based measuring techniques are developed [21, 231–233]. A FTS closed loop toolkit is developed and demonstrated the freeform machining with improved 50% form accuracy in Alvarez, sine wave and water drop workpieces [234]. Figure 27 shows the configuration OMSM to characterize the surface of freeform surfaces. A chromatic confocal sensor is developed for non-contact surface measurements along with the accuracy in nanometre level for an ultra-precision machine. This sensor provides the three-dimensional topography of flat and curved surfaces. The study of design and manufacturing of functional structured including the surface characterization, structures, biological surfaces, and patterns is facilitated using the closed loop feature based FTS patterning and measurement system [235]. The main advantage of OMSM is the measurement data is obtained without removing the workpiece from the machine. This help to eliminate the alignment errors caused during the loading and unloading of the workpiece onto the machine chuck. The manufacturing and measurement become more simpler than the other metrology techniques.

8. Manufacturing oriented design scheme

The ability to be manufactured, assembled, and measured is dependent on the optical design of a component. The tooling perspective should be considered in the design phase which can be the root step for successful manufacturing. Challenges in the fabrication of freeform optics are associated with the room space for the tool to work flexibly and tool tip contact the workpiece in every aspect. The main concern lies with large slope variations optics fabricated using ultra-precision machining techniques [236]. Problems like the existence and availability of specific tools that can perform the required machining without tool interference and provide all features to the component are still not focused. The cost of producing a freeform optic is much higher than that of a standard asphere or sphere [237]. The manufacturing time for freeform optics are often long, and the cost of raw materials is high i.e. huge blanks and discs.

As discussed in section 4, freeform optics based on best possible optical performance are often designed using the optical design software such as Code V, Zemax, etc. However, manufacturing technologies constraints are not considered during the design process which makes the process chain expensive and requires longer manufacturing period. Thus, the unfeasible design geometries along with the machining technologies constraint should be accounted at the early stages by the designers and the manufacturers. Garrard et al [238] structured the interface between the optimization engine and manufacturing cost metric computation which added functionalities to Code V. Program using Code V macro-Plus language was made for the prediction of the magnitude of non-rotational surface component of the sag as manufacturing cost. An integrated design and optimization environment that brought together the existing optical performance predictions with automated feedback of manufacturing costs for FTS machined freeform surfaces. Aderneuer et al [239] presented the CAD based tool for freeform micro-optical arrays which is able to visualize the difference between design and manufacturing constraints at the earlier stages of optical design. GA based manufacturing constrained design technique was proposed for the four mirror system [240]. In design, the manufacturing constraints such as position of all the mirrors and curvature radii of the mirror surface should be considered to reduce the machining time in ultra-precision raster milling.

9. Summary

Nowadays, almost in every optical system, freeform optics finds its significance and emerges as a hot research topic. By focusing on the recent and future demand of optics we review comprehensively the present state of the art of advances
in freeform optics, its design methods, manufacturing, metrology, and their applications. The optics, space, automotive, defence industries and many more are directly dependent on the time involved in the complete production of advance designed freeform optics. The freeform optics must follow 3F’s principle i.e. form, fit, and function. In achieving the 3F’s of the freeform optical components and freeform optical systems, time plays a major role. Therefore, particularly for freeform optics advanced economical processes should be developed that does not negotiate the designer’s efforts, reduces the time of assembly and testing and also reduces the energy consumption, and wastage of materials.

The optical design has been considered for several decades as the main theme for research, production, and teaching purposes. Freeform optical designs have proved to be more advantageous in balancing aberrations from optical systems than conventional designs, as well as allowing for more cost-effective optical system fabrication. Fundamentals lies in geometrical optics and paraxial optics that are described mathematically to generate a surface. Optical design for imaging applications are created and modified by solving the PDEs as the calculation of discrete light is possible. However, control over the chromatic aberrations in the optical system is not possible. Tailoring method considers limiting edge rays that tends to guarantee the transfers of complete properties of each ray travelling along the optical axis within the range of acceptance angle. Several 3D freeform optical surfaces for can be designed by solving the nonlinear PDE. The point-to-point mapping works on energy conservation and uses point-cloud to design optical systems. Division of surfaces into grids and its point normal vector is used to provide the relationship between the grids with specific shape, angle and quantitative cells to form a smooth surface. Design with SMS provides multiple surfaces generations at one time developed initially for non-imaging optics, especially for illumination. This efficient design method works on the principles of bundle coupling and prescribed irradiance to control energy distribution through single or group of optics. Latest advancement has led this method to develop freeform optical surfaces for applications such as concentration, light pipe, and many more. Recently, extended NAT for freeform optical design considers high-order polynomials and Zernike terms to cancel out the aberrations based on the image field. NAT based design are more flexible to the experienced designers as it requires deep mathematical understanding of the aberrations. Apart from aberrations, tolerance also play a prominent role in design of freeform, therefore, to lower the precision required during machining, tolerances should be a top priority. Newly introduced design-to-manufacture schemes are considering the manufacturing constraints during design phase to reduce the overall cost of the production and machining, measuring and assembly time.

Optical design with best solutions and high output performance are achieved by iterations where the values of design parameters value are modified. Today, the commercial optical design software has different algorithms for optimizations. Optical design software’s “user-defined surface” capability is extremely powerful and flexible, allowing for additional degrees of freedom in freeform optics design. However, the ray-tracing speed and optimization efficiency problems must be addressed in the future. Moreover, several functionalities are obtained that are accommodated in a single optics such as PAL. The Alvarez lens, whose principle is based on lateral shifting between two cubic form optics around the optical axis to adjust the refraction power, can vary the performance of an optic [241]. Such concept has been widely applied in different strategic and commercial applications over the previous two decades [242, 243]. In an ophthalmic application, a unique concept of the rotational varifocal lens is demonstrated, in which the two optical elements combine to provide the variation in refractive power. It is based on Alvarez’s concept, but with the inclusion of rotating motion between the two optics with freeform surfaces, the additional necessity of space is avoided [244]. The incremental steps towards miniaturization of optical components and systems by involving the freeform surfaces have led the researchers to revolutionize the way of abstracting more advantages from the existing optical materials.

The fabrication process routes have various challenges in terms of standard in alignments, tolerances, profile, waviness, and surface roughness. All the aspects must be considered in fabricating a complete optical product to extract more benefits. The diamond cutting methods with various configurations like STS, FTS, and hybrid ultraprecision processes are not the only effective and economical solution to fabricate the freeform optical surfaces but also the moulds for replication process of producing novel freeform optics in huge quantity. To maintain the form of the freeform optics, machining with advanced precision diamond tools along with precision modular drives are extensively adopted by most researchers and industries. It is also expected that this technology is being trusted for decades and its products are widely used in wide range of applications from space to biomedical. Although subtractive manufacturing i.e. grinding, milling, fly-cutting, diamond cutting, etc are generously used to fabricate such complex shapes. Recently, laser assisted SPDT is capable to fabricate rotational and non-rotational freeform surfaces in optical and IR materials. Shapes with large sag and depths like domes are achieved with ultraprecision milling and large freeform optics with the help of UPFC as there are machine holding limitation in terms of weight and size of optics. Development of freeform optical surfaces can also be achieved through advanced techniques of additive manufacturing and existing formative manufacturing to meet the need for prototyping and mass production with less time consumption and in various optical materials. Mass production reduces the cost as the quantity of products increase which cancel out the initial cost within a short period. For the purpose of smoothening and figure corrections, several new polishing technologies have been developed that can provide location specific corrections of optical surfaces without the generating SSDs. Various advanced functional coatings and methods have been developed to offer freeform optics a longer life and improved optical performance.

Surface shape metrology will continue to be in high demand as a vital enabler for conforming to manufacturing chain criteria. Metrology can be done in several ways such as in-situ...
monitoring and off-line testing during and after fabricating the components. Contact based metrology are the oldest adopted methods for surface measurements. Nowadays, profilometers with multiple axis are able characterize the 3D complex surfaces. They are preferred for long distance measurement. However, there are some issues such as wear of stylus makes this technology short span. Imaging technique for measurements are fast, precise and extremely sensitive to surface topography. Interferometry techniques have been used for more than hundred and still being developed. This technology has increased the precision and reduced the time of measurement as the test surface is captured at once and further analyses can performed on specific spot. Environmental factors such as moisture, temperature, etc may affect the accuracy of the measurements and chips remained after machining, lubricant, dust, coating on the samples also have influences on the measurement data. Whereas reflection based PMD technique is capable to measure large optics. Study of inner surfaces of optical test components were the main concern for the durability and performance of the transmissive and reflective optics. Inner defects emerged during and after the operations of abrasive based machining techniques are analysed by the laser scattering and optical coherent tomography techniques. The online monitoring possess fast acquisition and non-destructive nature and measurement techniques are more significantly in eliminating the alignments errors that are introduced during machining by clamping and unclamping of the workpiece optics. These strategies also make the surface characterization tasks easier than the traditional techniques. Mounting of measurement system on the ultra-precision machines for on-machine metrology has proven to reduce the characterization time and the errors produced by noise and vibrations of machine tools through the closed-loop compensation techniques. Measurement problems for freeform optics rises with the sag differences, slopes, depths, surface roughness, measurement speed, environmental factors, temperature control, and aperture size. Because of these factors the cost of the whole freeform optics increases, therefore a proper balance must be maintained between controllable parameters to keep the final products cost within limited range. Future scope of metrology lies in the development of measurement techniques for large slopes and depths of freeform optics, fast calibration of online measurement systems, integration of metrology with ultra-precision machines and artificial intelligence-based process optimization with online metrology.

Although tremendous progress in key fields associated with the freeform surfaces has been made by the researchers. Here are some specific challenges which remain untouched as follows,

- There is no such standard definition or tolerances for freeform surfaces that can be classified based on their performance. Is it possible to determine the relationship between surface roughness and specified tolerance at the design stage?
- Design can be accomplished with the help of commercial optical design software such as Code V, Zemax, etc however, the optimizations of complicated optical systems take a long duration of time to reach their optimum global solutions.
- Is it possible to develop a repeatable system for determining when and where the intended freeform optical surface should be positioned for optimal optical performance?
- For novel freeform optics, manual analyses of manufacturing constraints in design phase stands unreliable, impractical, and impossible. No doubt, there are custom software for freeform optics and will continue to become mainstream. However, fast and reliable solutions are required.
- As long as we want light, the demand for freeform optics will exists. How far we are to adopt complete solutions of sustainable manufacturing for the freeform optics?
- Development towards special measurement system for modern optics of any size and features that can perform all types of measurements. This can have benefits such as reduced cost, measuring time, complexity, wear, data-processing and increase in planning time and production.

In context of summary, the process route of development freeform optics essentially requires combine efforts of designers, fabricators, assembly, and testing unit to fill up the scientific, theoretical and practical gaps of advanced optics. Industries should focus to develop a complete machining centre with artificial intelligence and 5G technology which includes, grinding, milling, fly-cutting, polishing and coating. Such machines can be the key platform between design and final product.

Data availability statement

The paper has no associated data.

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Code availability

The paper has no associated code.

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Ethics approval and consent to participate

Research participants were not subjected to harm in any ways whatsoever. The respect for the dignity of all the research participants had been prioritized, and full consent was obtained from the participants prior to the research study.

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