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Positioning and alignment strategy in freeform mirror-based systems

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Abstract

System performance in optical, optomechanical, and optoelectronic systems is directly dependent on the precision level of positioning and alignment of the components. The location-specific placing of the optics plays a crucial role in limiting the energy loss in the Head-up display (HUD) system. The requirements for positioning and optical alignment become more stringent as the freeform optical elements, their functional and mounting surfaces with size and orientation become complicated along with the packaging restrictions get more severe. A simple sequential positioning and alignment technique that maintains the performance of HUD systems as per the required level is outlined. Three processes are involved in controlling the precision level i.e., (1) string-based mapping that provides accuracy upto 100's µm, (2) coordinate-measuring machine-based adjustments that offer position accuracy under 10's µm and (3) laser-based approach to maintain sub-micron positional accuracy. In spite of having certain challenges in terms of component handling and fixturing, this newly developed sequential stationing method (SSM) opens up new research directions that are inevitable for small-, mid-, and large-scale system integration.

Keywords: Alignment; Coordinate Measuring Machine (CMM); Laser; Positioning

1. Introduction

For building precision optical systems – especially for freeform reflective mirror-based systems, every single component is essential to be positioned with extreme accuracy to achieve high-quality imaging that corresponds to the optical design data. In the research and development phase of the optical, optoelectronic, and optomechanical instruments, a variety of certain errors can arise during the positioning and alignment of the components in the system. Besides the deviation in the form of each freeform optical surface, surface quality, and integrity, the physical and mechanical placement of each non-symmetrical optic could be the cause of degradation of imaging quality. The computational, mathematical i.e., positional data conversion, and mechanical errors such as the centration and tilt errors concerning the fiducials planes, zenith point, and form error deviations along the optical axis need to be considered for the better functioning of the system.

The optical component has a specified axis by default since it is often defined as a portion of a rotationally symmetric "parent" element. Although a more accurate view would refer to the off-axis component as the "child" element, historically often referred to the symmetric curve as the "parent" curve and the off-axis portion as the "daughter" element [1]. The “flare spot” alignment method was a simple optical system tilt and decenter detection with low powered laser [2]. Systems containing freeform surfaces mostly adapt to the off-axis portion.

Freeform optics stands different from conventional spherical, aspherical, and conics in terms of functionality and additional features that come with compact size and minimum complexity in system integration [3]. The challenges in the development of freeform optical systems are not only in design, fabrication, measurement, and surface integrity but also in the positioning and alignment of the components for functional testing and complete utilization.

When performing aligning operations in an optical system with rigid supports and depending on the mechanical and optical measurements of the precision surfaces, new difficulties emerge [4, 5]. The capacity to put the optical component in the desired location, knowledge of the optical properties owing to measurement machine error, and damage to the optical surfaces are a few critical challenges in the positioning and alignment of freeform optical systems.

A point of symmetry about a reference axis should be defined in order to measure a Centering error. The measurement process is referred to as "Measurement in Reflection" when the optical surface's radius of curvature is used to calculate centration errors [6]. Due to the non-symmetrical nature of the freeform surface, it becomes tedious to eliminate or control these mechanical errors. Therefore, multiple referencing with fiducials (i.e., planes and points) must be considered for the positioning and alignment. With this approach, the system integration can be done accurately but consumes more time than the systems with conventional optics. Thus, there is a need for a simple, fast, step-step approach that sequentially improves the precision level of the placement of the optical components for high performance in the HUD system. In this research work, an SSM is provided utilizing multiple platforms to limit the mechanical errors in a freeform optical system and avoid direct or indirect contact damage to the functional/active aperture of the optical components and fixtures.

In view of this, the following structure and methodology were chosen: In section 2 the basic concept and strategy are presented especially the approach developed to position the freeform optics HUD system. A description of the SSM along with the design, manufactured product, and fixturing for the functional testing is revealed in Section 3. The results in terms of positional and angular errors of each component with different approaches are provided in Section 4. Based on this research carried out, succinct research conclusions are given in Section 5.

2. Methodology

Precise positioning and alignment of the optical components and the optical beam is critical for imaging performance in HUD systems. To achieve optimum optical performance for the HUD image projection, it is essential to design a precise position and alignment scenario, including transverse alignment, and longitudinal alignment through measurements. The basic concept of the SSM for components in HUD systems is:

- String-based mapping for the initial placement of the freeform optics and devices as per the design data to detect the chief ray.
- Coordinate metrology-based placement of the components for improved precision level of positioning in a system.
- Laser-based positioning to precisely control the centration and tilt errors.

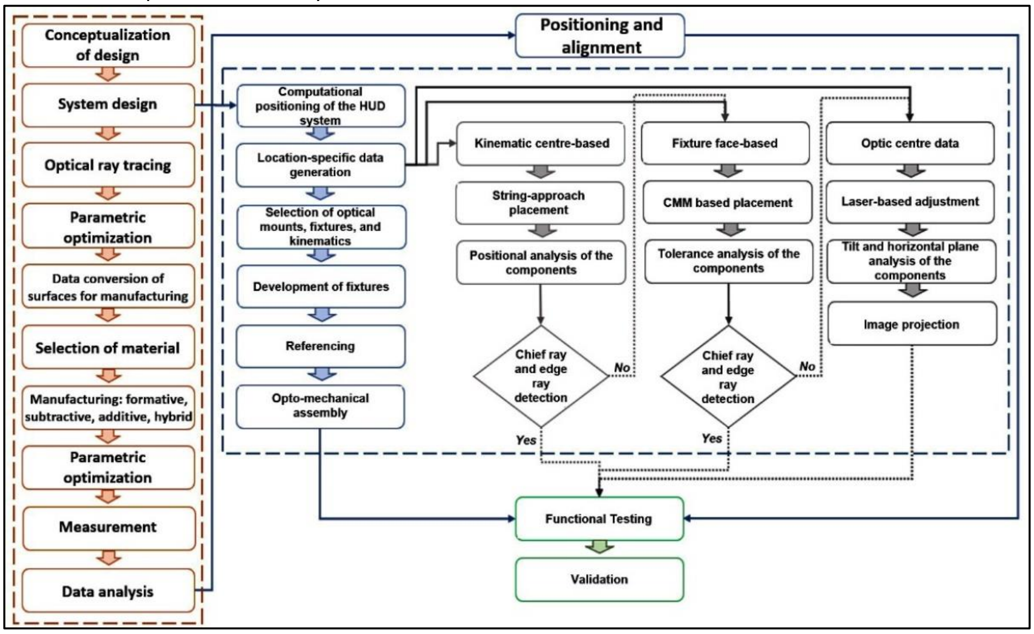

Figure 1. Strategy for positioning and alignment of optical components in HUD system.

The novel stationing strategy combines both mechanical (i.e., contact measurement feedback) and optical (i.e., non-contact measurement) modes for locating the precision components held on fixtures and kinematics. In this method, three different phases are sequentially implemented to avoid any chance of surface imperfection such as scratches, digs, etc. on the clear apertures of the freeform mirrors. Because manufacturing the complex freeform mirror requires more time and money than producing the symmetric optical components. Not only manufacturing and metrology are critically difficult for such surfaces but handling these optics is a significant obstacle to a product's sustained life. Therefore, a methodical strategy is presented that comprises two stages of contact referencing. The first stage involves a string-based technique for kinematics placement, followed by coordinate metrology for bringing the active aperture into the micron-level range concerning the design data coordinates. The final phase is the laser-based non-contact alignment which precisely balances the components in the systems. Figure 1 illustrates the complete developmental process route for the HUD systems, however, only position and alignment strategy are expanded in this research.

3. Strategy for positioning and alignment of freeform optical components

In the development of the freeform optical system, all phases under production are dependent on the design data. A few common challenges for open system testing include (1) freeform surface referencing; (2) sufficient space for fixtures and mounts to hold the delegate optics while adhering to design data coordinates; (3) external temperature fluctuations; and (4) type of environment. Implementation of SSM in HUD testing and final assembly may also have certain risks including surface contamination, dust particle deposition on the active surface, collision, and collapsible fixtures and components. In this Section, different modes to position and align the component and optical beam are described.

3.1. *Design data*

Typically, a system's design data is obtained as coordinates that are subsequently separated into many subsets for the independent construction of subsystems. On the other hand, an increase in reference points, planes, and data conversion could further complicate the process of assembling and testing a system for optomechanical engineers. The first step is to designate a single element in a system as the referenced point of the plane. In this case, the centre of the Eyebox serves as the pivot point for the sub-systems and is represented as a constant point in Figure 2(a). The current HUD system contains two freeform mirrors for directing the light beam toward the Eyebox via. Windscreen. Referencing facilitates the quick identification of the chief and edge rays of various freeform optics and eases the mathematical calculation of the remaining optical component placements.

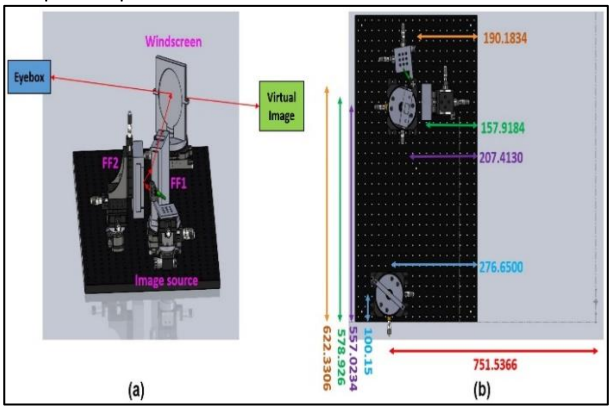

Figure 2. Freeform HUD system, (a) 3D model including the schematics of chief ray and (b) kinematic centre-based coordinates from referenced Eyebox centre.

Table 1 Position of the components of HUD system design obtained through multi-parameter optimization.

Components	Description (Clear aperture)	Dimension (mm)	Angle (°)		Position (mm)	
			H*	V^	H*	V^
Eyebox	Rectangle	130 X 130	093.000	003.000	0	0
Windscreen	Circle	88 Ø	134.860	044.860	757.5366	009.8609
Freeform mirror 1	Rectangle	90 X 100	52.8155	37.1845	682.3179	466.5543
Freeform mirror 2	Rectangle	60 X 80	70.3155	19.6845	632.8050	488.4569
Image source	Rectangle	35.04 X 28.03	59.3155	30.6845	665.0700	531.8615

H* – Horizontal
V^ – Vertical

For ease in calculation, the design data coordinates of components in the sub-system are converted in terms of the position and angle with respect to 90° horizontal and 90° vertical imaginary planes as listed in Table 1. The simplification of the element's location in the sub-system reduces the actual time for the assembly and optical testing. Also, it adds referencing coordinates for the freeform system which is predominantly required for complex highly valuable systems with multiple components.

3.2. Kinematic centre-based

Kinematics plays a critical role in the system testing at the R&D phase. For successful testing of freeform optical systems, precise movements of the components in required degrees of freedom are essential. Initially, the kinematic mounts and reflecting optics are placed with fixtures on the testbed using a manual placement technique, which is referred to as a string-based method. This technique is more advantageous than the single ruler and scale as the intersection of the strings gives the actual center of the kinematics. The plane that passes through the optic's centre is then further adjusted using the first referenced point, or the Eyebox centre point, as indicated in Figure 2(b), or the length of the kinematic side face. The problem with this method is that it cannot support an off-axial mount or optics on a kinematic mount. To increase the degrees of freedom for optics, multiple mounts are often tightened, either on the base kinematics mount or one above the other. In this instance, the string-based method provides the first marking, and the other adjustments are made by the computation that determines the optics centre plane using trigonometric functions. When the system design has optics location coordinates in proximity to other components, then off-axial fixturing is recommended.

3.3. Fixture referenced approach

Once the freeform optics and devices are positioned close to the required coordinate (with the highest manual adjustment precision level) then the Coordinate Measurement Machine (CMM) is utilized for further reduction in the closeness to the nominal value calculated from the design data. The measurement values are obtained from the side face of the kinematic mounts, and as Figure 3 illustrates, a CMM (ZEISS PRISMO ACCESS) can achieve a measurement accuracy of 1 µm. However, the true component placement is close to the machine's measurement repeatability. Geometric inaccuracies in the mounting, fixturing, and manufacturing process of these components may result in substantial variations in measurement results. The main challenges with this technique are; (1) long tracing path setup time, (2) maintaining stable temperature, (3) contact type measurement which may induce surface imperfection on the precision freeform optics, (4) sufficient gap between the components for clean travel of the probe, and (5) proper handling of the measurement probe tip. Also, a quick solution in terms of measuring the sub-system's positional coordinates would be laser and computed tomography scanning as the capturing points are exceptionally more than the points obtained from the tactile CCM technique. The CT scan provides quick solutions for part analysis, however, when the large-sized (i.e., centimeter- and meter-class) systems with large spacing between components the CMM is preferred due to low instrument cost.

Figure 3. Coordinate metrology-based positioning and alignment of the freeform mirror-based HUD system.

3.4. Optics centre data

Detection of the chief ray for symmetrical optical objects such as spheres, conic, and aspheres is widely implemented by controlling mechanical errors such as centration and tilt. However, the centration error is not observed in open system testing and assembly. The presence of tilt on freeform optics is the prime focus to control with a Laser-based approach. There are three objectives for adapting this technique for the freeform optical HUD system i.e., (1) detection of chief ray, (2) control over tilt and tip of the non-symmetrical surfaces, and (3) functional testing. Functional testing of the HUD system is performed by projecting the laser and capturing it in the required magnified form. The beam spot diameter is calculated theoretically and compared with the captured image of spots at the entrance pupil diameter of 8 mm. The optical fibre diameter is selected as per the pixel size in real image projection in 2D image simulation.

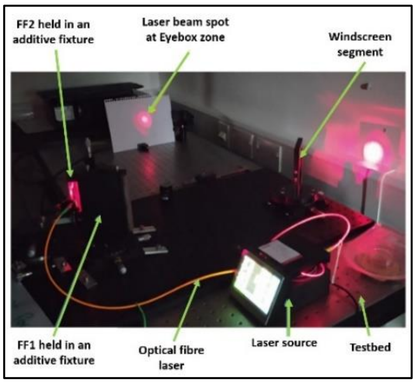

Figure 4. Laser-based alignment for HUD system.

The optical alignment and the functional testing of the freeform mirror-based HUD system using the low-powered laser as shown in Figure 4. Initially, in this experimental research, the tilt is removed by comparing the laser beam spot from different field angles. The projection was performed for the laser source and freeform mirror 1 due to their off-axial mountings on the kinematics.

4. Results

To demonstrate the novel SSM for the freeform HUD system, a few positional results are presented in Table 2. The positional errors are obtained from string-based and CMM approaches to put the components in the desired place. The optical components are stationed more systematically with string-based in the range of 100's µm precision and further reduced to 10's µm with the Coordinate metrology-based approach.

After the placement of the optical component with the best achievable human and mechanical machine ability, the next phase is the optical alignment of the elements in the HUD system. The alignment and the testing of the freeform HUD system using the low-powered laser are described in Figure 5. The magnification factor and measurement of the laser beam spot diameter are reported in Table 3.

Table 2 Positional values of the fixture face-based components in the HUD sub-unit system measured using CMM.

Components	X (mm)				Y (mm)				α_x (°)			
	(A)	(B)	(C)	(E1)	(A)	(B)	(C)	(E1)	(A)	(B)	(C)	(E1)
Windscreen	276.6500	276.7480	276.6381	0.012	-100.1500	-100.2149	-100.1528	0.0028	134.8600	135.1850	134.7270	0.133
Freeform mirror 1	230.1609	230.2395	230.1903	-0.0294	-574.3027	-574.2791	-574.3024	-0.0003	52.8155	52.1265	53.0001	-0.1846
Freeform mirror 2	80.4702	080.3838	80.4647	0.0055	-551.2191	-551.1722	551.2000	-0.0191	70.3155	71.0365	70.1065	0.209
Image source	211.6641	211.6048	211.6728	-0.0087	-700.4909	-700.4544	-700.4908	-0.0001	59.3155	59.8105	59.1423	0.1732

(A) - Nominal

(B) - Measurement readings from String-based method

(C) - Measurement readings from Coordinate metrology-based method

(E1) - Error = **(A)** – **(C)**

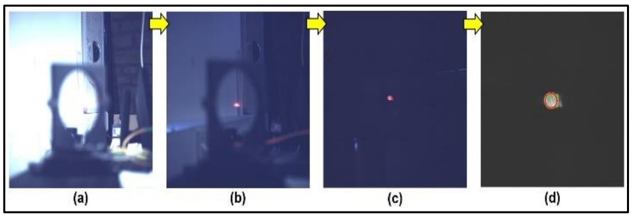

Figure 5. Laser-based alignment and functional testing of HUD system, (a) focus with lens at 3000 mm, (b) laser beam at centre of the windscreen, (c) laser spot at 0,0 field angle captured with an entrance pupil diameter of 8 mm, and (d) equivalent circular diameter of the original image.

Table 3 Laser-based alignment and functional testing with beam spot diameter at (0,0) field angle.

Image name	ECD (Pixels)	Image Pixel size	Beam Diameter (µm)	
			Theoretical	Experimental
O	51.6	4.179	75.7	215.6364
O1	50.6	4.179	75.7	211.4574
O2	48.1	4.179	75.7	201.0099

ECD – Equivalent circular diameter

5. Conclusions

The proposed strategy can be applied to various optical, mechanical, and electrical systems at the R&D phase as well as for the system functional testing. The major contribution of our approach for positioning and alignment finds potential relevancy in precision system development and has great potential in aspects of rapid, preventive, and optimistic freeform optical system integration for different applications. Some of the key features of the SSM are as follows,

- String-based placement of the components results in a precision level 100's µm.
- Coordinated metrology-based positioning is capable of further improving the precision level under 55 µm of the component placement in the system assembly and optical functional testing.
- Laser-based approach to control the alignment and position of the freeform components tilt under 0.0138 degrees and centration in submicron precision level.

The SSM strategy reduces the number of collisions and collapsibility of optical components and fixtures required for positioning and alignment to a minimum or negligible in complex optical systems. While fewer mechanical adjustment devices are needed, the cost of system development decreases. Also, it reduces processing time and improves accuracy in a step-by-step manner which gives numerous opportunities for different applications depending upon the level of precision required. Future work includes optimization of SSM for various precision settings.

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