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Performance and Tolerance Sensitivity Optimization of Highly Aspheric Miniature Camera Lenses

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ABSTRACT

Miniature camera lenses are currently manufactured at volumes over 1 billion units per year. In this high volume industry, design methods that improve tolerance to manufacturing errors result in improved yield and significantly reduced cost. Few, if any, design for manufacture methods have been developed for this solution space, which is vastly different than traditional design as it is dominated by highly aspheric optics and compact design forms. In this paper, five design for manufacture methods that were developed for traditional designs are examined for their efficacy in improving the as-built performance of a well-corrected injection molded miniature camera lens. Building on the results of the evaluation, a new design for manufacture method is developed which is highly correlated to the sensitivities associated with this solution space and requires little computational overhead. The new method generates 1.3 times the number of improved solutions and produces a design with 1.7X looser tolerances than the starting point.

Keywords: design for manufacture, desensitization, lens design, plastic, injection mold, asphere, mega pixel, miniature camera

1. INTRODUCTION

Lenses for miniature cameras are manufactured in volumes exceeding 1 billion units per year in 2009¹ and are ubiquitous in platforms ranging from cell phones to laptop computers. In an industry this large, lens design decisions have an incredible impact on cost. The full production cost is a function of many parameters including the number of elements; cost of materials; capital investment for fabrication, assembly, and metrology; time and material cost for mold re-work and other iterative improvements; time for assembly and test; and yield. Given that a design form and manufacturing method have been selected to meet the design requirements and cost goals, the production yield becomes the dominant variable in the cost equation.

The lens yield is a function of the as-built performance requirements and the as-built performance. The as-built performance is dependent on the manufacturing tolerances, the sensitivity of the design to perturbation according to the tolerance distributions, and the design residual error. Too often, the lens designer approaches this relationship by reducing the residual error as much as possible, performing a tolerance analysis, and specifying tight tolerances on the drawing in order to meet the as-built performance objectives with high yield. Since the only compensator typically available for these systems is focus, it becomes the manufacturer's responsibility to tighten tolerances through process control in order to improve yield.

A typical miniature camera lens intended for a 1/4" format CMOS detector images a 60 degree full diagonal field of view with an image height that is nearly $1/10^{\text{th}}$ that of the standard 35 mm format. Thus, to achieve similar imaging performance to the 35 mm objective lens counterpart, the tolerances must be reduced by $1/10^{\text{th}}$.² To this end, manufacturers invest heavily to tune the design of mold cavities, improve metrology capabilities, and apply novel fiducial strategies to improve the molding and assembly process.^{3,4} The challenge continues to become greater as heavier demand is placed on smaller form factors and reduced cost.

It is the lens designer's responsibility to alleviate the manufacturing burden as much as possible by applying design for manufacture (DFM) methods to create designs which meet the as-built performance criteria with reasonable tolerances.

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Many methods have been developed to desensitize the design of traditional lenses. Understanding that these methods were not intended for the solution space occupied by the highly aspheric plastic lenses used in miniature cameras, in this paper we investigate adaptations of these techniques for their efficacy and develop a design for manufacture method that is tuned for this unique space.

The rest of the paper is divided into four parts. In section 2, we describe the method of analysis: the lens that is the subject of investigation, the components of the optimization that are common for all methods, and the evaluation of as-built performance. Section 3 describes six design for manufacture methods and their implementation. In Section 4 we compare the as-built results of the methods. Conclusions and observations are provided in Section 5.

2. METHOD OF ANALYSIS

To provide a fair comparison between design for manufacture methods, a single base lens was designed and is used for all investigations. A common optimization routine is constructed to meet the general design requirements and adapted as needed for the specific DFM method.

Since damped least squares (DLS) effectively optimizes from the starting point to a nearby local minima, little insight can be gained by comparing the methods using DLS optimization alone. This will more likely demonstrate that one method is well-conditioned to warp the solution space effectively for *that particular starting point*, whereas the others are not. Instead, a larger set of related designs is compared by using a deterministic global optimizer such as Code V's Global Synthesis®, allowing each method an opportunity at directing the progress of the global optimizer away from the starting point toward a better region of solution space. To achieve this, the common optimization routine is used for each method in a six hour global optimization using Global Synthesis® on the same computer, using one processor. Each set of solutions is then evaluated with the same criteria.

2.1 Design requirements and base lens

The lens under investigation is a well-corrected objective intended for a 1/4" format 3MP CMOS sensor with 1.75 micron pixel pitch. The lens specifications are those presented by Bareau and Clark², with a few exceptions on chief ray angle, optical track length, and back focal distance. With current micro-lens shifts, chief ray angles larger than 22 degrees may be employed⁵ and that of 25 degrees is used in this design. The required optical track length, measured from the vertex of the first surface to the image plane is reduced from 5 mm to 4.9 mm to ensure that the assembled lens with tolerances and focus adjustment will have a 5 mm TTL; not exceptionally aggressive by today's standards. A back focal distance requirement is added to the list of specifications to ensure there is room for a typical 0.5 mm IR cut filter, a sensor cover glass, and margin for focus adjustment. The full list of design requirements is provided in Table 1.

Table 1. Lens requirements for 1/4" 3 megapixel CMOS sensor.

Parameter	Requirement
Effective Focal Length	3.8 mm
Entrance Pupil Diameter	1.36 mm
f/number	f/2.8
Full, Unvignetted FOV	60 degrees
Image Circle Diameter	4.6 mm
Wavelengths	486nm to 630 nm
Optical Track Length	4.9 mm
Back Focal Distance	≥ 1.4 mm
Optical Distortion	< 2%
Chief Ray Angle	≤ 25 degrees
Relative Illumination	> 50%

The lens that meets these requirements is a 4 plastic element design adapted from the author's previous work designing a miniature camera objective from the starting point of a landscape lens.⁶ This design form is not limited only to 3 MP sensors, but is representative of a large class of well-corrected multi-megapixel miniature cameras. This base lens is used as the starting point for all DFM methods and is shown in Figure 1.

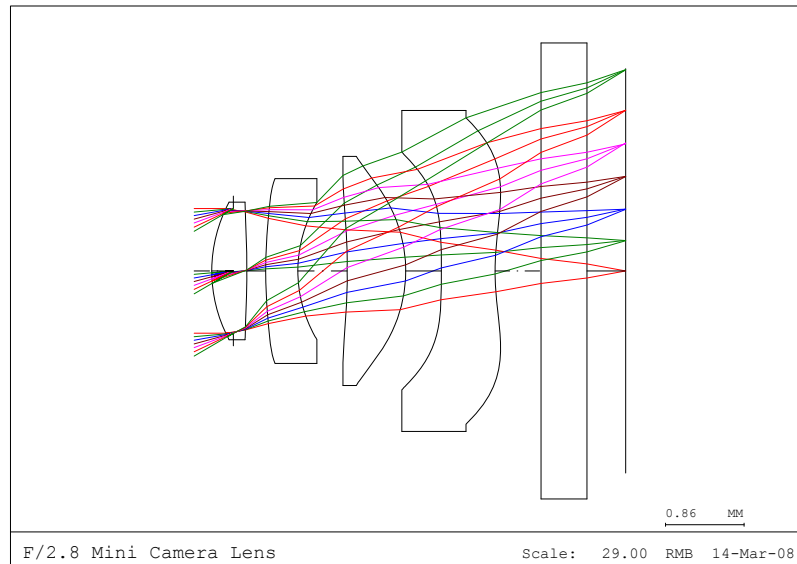


Figure 1. Base lens design with floating aperture stop for 1/4" format 3 MP camera.

2.2 Common optimization constraints, variable set, and figure of merit

Since a common optimization routine will be used for all methods, it should provide the necessary design constraints without biasing the design toward a particular desensitization method. In this optimization, element edge and center thickness are constrained to be greater than 150 and 350 microns, respectively. The center thickness to edge thickness ratio is constrained to be less than 3:1, according to Beich's limits of fabrication⁴. Additionally, each surface is constrained to have a maximum slope of 45 degrees for mold manufacturability. Distortion is not intended to be a performance driver and is held to less than 1.5% to provide some margin for meeting the design requirement. The effective focal length is set by the image height for the extreme field.

The base design is meant to provide the most flexibility to the global search routine for finding new solutions, so all curvatures, conics, materials, thicknesses, and asphere coefficients (from 4th to 12th order on each surface) are allowed to vary. Twelfth order aspheres are generally considered bad practice for standard fabrication, but molded plastics produce highly aspheric surfaces without much difficulty. Aspheres with higher orders are not used because nearly diffraction limited solutions are possible with 12th order. The materials of the lens are allowed to vary within the convex polygon described by POLEFINH, polyetherimide 1010 (PEI), polycarbonate, SAN, and acrylic, with refractive index information verified across several sources^{7,4,8,9}. The stop position is allowed to float. Both the material and aperture stop variability remove the optimized lenses from physically realizable solutions, but neither is a significant obstacle to fix for a select design with minimal impact to performance after reoptimization.

The figure of the merit for the optimization is RMS WFE calculated about the centroid for seven field points (0, 5, 10, 15, 20, 25, 30 degrees) with equal weight and for three wavelengths (486, 550, 630 nm) with equal weight. Although MTF is a more desirable figure of merit for this lens, it is currently not applicable to global optimization; RMS WFE is used as it tends to produce solutions with generally favorable MTF.

2.3 As-built evaluation

The tolerances used for analysis are presented in Table 2 and correlate to those published by Renkema³. This set of tolerances may be difficult to achieve in mass production; they are used here to provide relative comparisons. All of the tolerances are implemented with a uniform probability distribution.

Table 2. Precision tolerances for plastic molded lens.

Parameter	Tolerance
Center thickness	$\pm 3 \mu\text{m}$
Flange, spacer, air gap thickness	$\pm 3 \mu\text{m}$
Axial surface displacement	$\pm 3 \mu\text{m}$
Radius of curvature	$\pm 3 \mu\text{m}$
Surface Decenter	$3 \mu\text{m}$
Surface TIR	$3 \mu\text{m}$

There are notable omissions from the set of tolerances in Table 2. Element decenter and element tilt are not included in the set, as they are largely redundant with surface decenter and tilt in their effect on the wavefront error. Surface form error is a significant contributor to as-built performance, but is also a practical omission. Surface form error of a specified peak-to-valley magnitude or RMS value has an infinite number possible profiles, each with a different effect on the as-built performance, depending on the location of the surface in the design and the form of the error. For this reason, it is only useful to analyze a statistical set of form errors targeting a select RMS or p-v value – for each solution. The response of the full statistical set of form errors is then an indicator of the solution's sensitivity to form error. An early investigation of this sort showed that none of the methods significantly influenced the sensitivity to form error.

After the optimization is run for six hours, the set of results is analyzed. For each solution, the program executes a fast wavefront differential tolerance analysis using defocus compensation and records the nominal RMS WFE and as-built RMS WFE for each of the seven field points. The as-built RMS WFE is the value attained for a cumulative probability of 0.977, meaning that 97.7% of the systems built with the given tolerances are predicted to have RMS WFE less than or equal to the as-built RMS WFE. Sensitivity to fabrication errors is calculated as the nominal RMS WFE subtracted from the as-built RMS WFE. Nominal, sensitivity, and as-built RMS WFE is averaged over field and wavelength to reduce the data set and remove any bias toward methods that desensitize particular fields at the expense of others. Any lens with a nominal RMS WFE greater than one wave is considered a poor solution and not included in the analysis. The nominal field-averaged WFE for the base lens is 0.096 waves RMS and the as-built WFE is 0.172 waves RMS.

3. DESIGN FOR MANUFACTURE METHODS

Through 150 hours of global optimization with many variations on DFM methods, five implementations are selected as the best in their class and one new method is developed; these DFM methods are described below.

3.1 Method 1: Global search and as-built ranking

In 2006, McGuire described an approach for discovering lenses with good as-built performance¹⁰. This method uses a global search optimization to generate many solutions without attempting to direct the solutions toward being insensitive to fabrication errors. The results are then sorted for the design that performs best after tolerance analysis. The method is implemented with no change to the merit function or the lens.

This method is critically important for the purposes of this investigation because it establishes the set of random, unbiased solutions within this particular design space. Any methodology that intends to influence the sensitivity of the lens is compared against this standard for its effectiveness.

By analyzing the average sensitivity of the solution set to each of curvature, thickness, tilt, and decenter perturbations as well as the combination of all

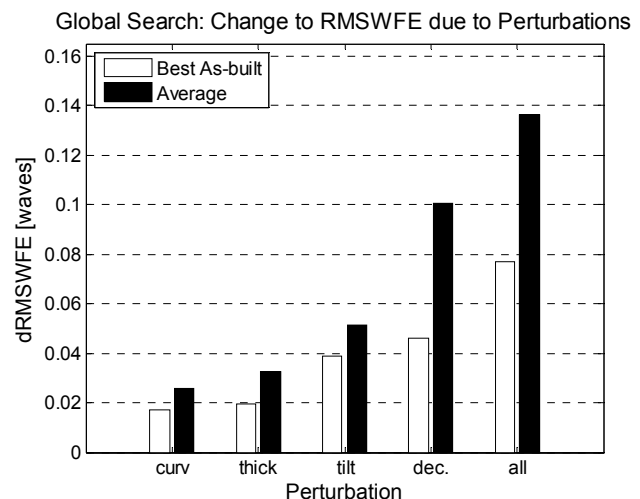


Figure 2. Sensitivity to perturbations for the lens demonstrating the best as-built performance and average of solutions from global search method.

perturbations, we see that sensitivity of this solution space is dominated by decenter perturbation, as shown in Figure 2. The lens demonstrating the best as-built performance does so primarily by greatly reducing the sensitivity to decentration.

Since this set of solutions is unbiased, it is also useful to extract the design with the best nominal performance from this set. That design has a nominal WFE of 0.031 waves RMS and an as-built WFE of 0.197 waves RMS. This is the design that would have been selected based on nominal performance alone; 40.5% of the lenses – even in this undirected approach – have better as-built performance.

3.2 Method 2: Full differential wavefront error integrated optimization

On the other end of the spectrum from the global search and as-built ranking DFM method is one that attempts to control the as-built performance directly in optimization by integrating the complete tolerance analysis into each optimization cycle. This method is implemented by including CODE V's AS_BUILT_VAR function as a user-defined operand in the merit function with a flag set to use only the rays traced by the base optimization routine to increase speed. The operand is capable of returning many values from the tolerance analysis, including the probable change to the wavefront error (i.e. the sensitivity) and the probable as-built wavefront error. Although we desire to optimize the as-built wavefront error directly, we found better results when optimizing with a merit function defined by equally weighted performance and AS_BUILT_VAR sensitivity figures of merit.

3.3 Method 3: Reduction of ray angle of incidence and refraction

In 2003, and updated in 2006, Isshiki described a method for optimization of performance and tolerance sensitivity deemed 'θ-segmentation'.^{11,12} This method intends to find tolerant lens solutions by adding to the merit function the sensitivity to sample ray incidence and refraction angles at each surface. The sensitivity term, θ, added to the merit function is given by

$$\theta = \sqrt{\frac{\sum_{s=1}^k (i_s^2 + r_s^2)}{2k}}, \quad (1)$$

where i_s and r_s are the sample ray angle of incidence and angle of refraction measured at each surface. The summation is taken over all surfaces, k , and normalized by the twice the number of surfaces. The sample ray is suggested to be the marginal ray to the image center and the upper and lower rim rays to the image corner.

Once the sensitivity term is in place, the multidimensional solution space is searched with a global exploration technique utilizing a Gaussian escape function described in an earlier paper¹³. The somewhat broad search space is consistently refined by constraining each solution to have a θ smaller than the previous solution by some incremental step. For example, the first solution could be constrained such that $\theta < 30$ degrees; the second solution is then constrained to the search space where $\theta < 29.5$ degrees, and so on.

A variation on this approach is mentioned by Jeffs whereby the change in direction cosine of a ray entering and exiting an element is reduced¹⁴. The sensitivity term in this case is given by

$$\Delta m = \sqrt{\frac{\sum_{i=1}^e (m_i - m_i')^2}{e}}, \quad (2)$$

where m is the ray direction cosine before the element, m' is the direction cosine of the ray after the element, and the summation is taken over all elements, e .

Before implementing either of these DFM methods, both of the proposed metrics are analyzed for the chief (R1), upper (R2), and lower (R3) rim rays of all field points (F1-F7) for the solutions generated in Method 1. The value of each

metric is then correlated to the sensitivity of the set of lenses to determine the metric and the ray which hold the best potential for describing the lens sensitivity. The results are shown in Table 3; the analysis shows that the θ metric using the upper rim ray from the 5 degree field point provides the best correlation to sensitivity with correlation coefficient around 0.35.

Table 3. Correlation coefficients for the sensitivity term, θ , and calculated RMS WFE sensitivity to perturbation. The ray with the highest correlation is indicated in parenthesis (e.g. R2F2 indicates the upper rim ray traced for field 2).

Metric	Perturbation				
	Curvature	Thickness	Tilt	Decenter	Combined
θ correlation to sensitivity	0.52 (R2F5)	0.42 (R3F3)	0.46 (R2F4)	0.27 (R2F2)	0.35 (R2F2)
Δm correlation to sensitivity	0.43 (R1F6)	0.37 (R3F3)	0.34 (R1F2)	0.26 (R2F2)	0.29 (R2F2)

Having selected the sample ray for computing the sensitivity term, θ , the optimization process involves solution space searches constraining $\theta < \theta_L$, where θ_L is the ray angle limit confining the search space. For the purposes of evaluating these methodologies on near equal footing, the technique employed by Isshiki is adapted for use with the Global Synthesis® (GS) optimization instead of a global optimization driven by a Gaussian escape function. This is implemented by first running GS for 40 minutes with $\theta_L = 18.5$ degrees. The best solution is then selected for the next 40 minutes GS run with $\theta_L = 18$ degrees. This process is repeated and θ_L is decreased in half degree increments until 9 GS runs have been performed so the total time is six hours (as it is with all other methodologies) and the final value of θ_L is 14.5 degrees. The lens with the best as-built performance occurs for $\theta_L = 15$ degrees.

3.4 Method 4: Reduction of tilt-induced axial coma

In 1965, H. H. Hopkins and Tiziani studied centering errors of optics and derived a formulation for computing axial coma for such errors.¹⁵ In 1970, David Grey used their work to establish a method of optimization for reduced sensitivity to tilt by minimizing the impact to axial coma by each surface in the design.¹⁶ Grey's approach notes that the path length change caused by a surface displacement is given by

$$\Delta OPL = \vec{D} \cdot \vec{N} (n \cos(i) - n' \cos(r)), \quad (3)$$

where $\vec{D}$ is a vector describing the surface displacement, $\vec{N}$ is the surface normal vector, n and n' are the indices of refraction before and after the surface, i is the ray angle of incidence and r is the ray angle of refraction.

To reduce the sensitivity of the system, the value of ΔOPL is computed for many rays from a field angle and the average value of ΔOPL is subtracted as this has no optical significance. Next, the component of ΔOPL that is linear with the height of the ray in the entrance pupil is removed, as this component corresponds to a shift of the image position. Finally, the variance of ΔOPL is reduced in order to reduce sensitivity to tilt.

This method is implemented through the use of the SNS operand in Code V, which directly calculates ΔOPL for each surface given a tilt perturbation. The contributions from all surfaces are RSS'd to produce a constraint in the merit function which is targeted to zero with a weight equal to that of the performance merit function.

3.5 Method 5: Desensitization through zoomed configurations

In 2003, Fuse patented a general procedure to simultaneously optimize performance and sensitivity by generating a perturbed configuration for each positive and negative implementation of each tolerated value.¹⁷ With a minimum of 8 configurations for each surface (for +/- curvature, tilt, thickness, and decenter perturbations), this would require at least 64 configurations in addition to the nominal design and would be prohibitive even for six hours of global optimization.

More recently, Rogers developed a less computationally expensive version of this approach in which all parameters are adjusted simultaneously in each perturbed configuration¹⁸; each parameter is perturbed to its maximum magnitude with a randomized direction – this means sign for curvature and thickness, orientation for tilt and decenter. In the implementation of this approach, care is taken to ensure that as the lens is optimized, the perturbed configurations

maintain their deviation from the nominal configuration according to the tolerance value. Each configuration is allowed its own focus compensation so that sensitivity to defocus is not overly weighted.

This method is implemented with both 3 and 4 zoom configurations added to the nominal design. Since there is significantly more computational burden required for each additional configuration, the best results are found with 3 zoom configurations, as more solutions are generated in the same time.

3.6 Method 6: Reduction of decenter-induced differential wavefront error

Observation of the results of the methods above shows that the best DFM approach would be fast enough to produce many results and highly correlated to the perturbations contributing to the lens sensitivity.

As demonstrated by Rimmer, the displacement term in equation (3) may be computed for the full set of curvature, thickness, tilt, and decenter perturbations to quickly calculate the sensitivity to these errors.¹⁹ In fact, the differential wavefront error (dWFE) calculated in this way is used to generate the results for Method 2 which are highly correlated to the lens sensitivity. Although this calculation is fast for analysis it applies additional computational burden when used in optimization and reduces the number of solutions that may be generated in a given time.

To improve this DFM method, we first note that the as-built performance of this class of objective lenses is greatly affected by sensitivity to decentration errors, as demonstrated in Figure 3. For this reason, an operand is constructed to compute the differential wavefront error according to equation (3) above only for surface displacement created by decentration.

The operand is tested through a correlation analysis as was performed for Method 3. For each solution generated by the global search method, a set of rays is traced for all field points and the differential wavefront error for decentration is calculated for each surface. The result is RSS'd over all surfaces and averaged over field. It is found that a ray set reduced to 5 rays still maintains a high correlation coefficient of 0.85 to decenter sensitivity. The computational burden is further reduced by evaluating only the axial field, with a correlation coefficient of 0.80.

4. COMPARISON OF RESULTS

The six design for manufacture methods described in Section 3 generated a total of 1106 lenses for evaluation. The total number of lenses is shown for each method in Figure 2, along with the number of lens solutions generated with as-built WFE less than 0.17 waves RMS; that is, better as-built performance than the starting point.

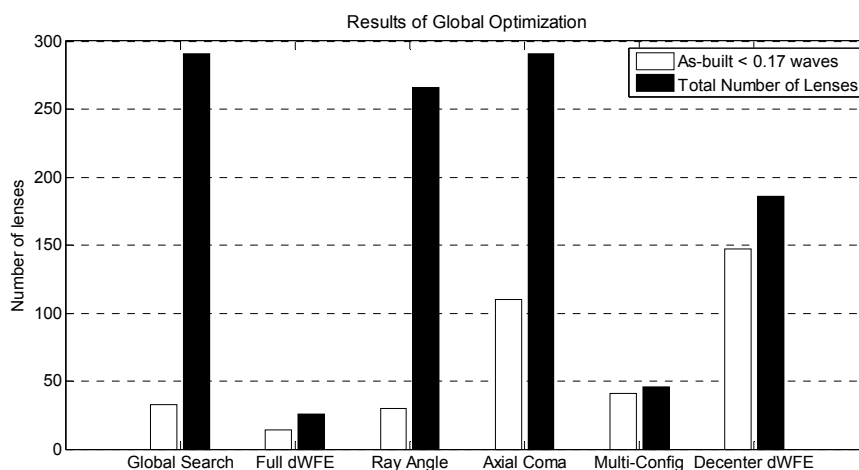


Figure 3. Number of lenses with improved as-built performance and total number of lenses generated by each design for manufacture method after six hours of global optimization.

Although the multi-configuration method does not produce many lenses in 6 hours due to computational overhead, the method is highly correlated to lens sensitivity and, therefore, very effective; 90% of the solutions have better as-built performance than the starting point. The axial coma method creates little computational burden - producing as many solutions in 6 hours as the undirected global search method - while also generating 110 solutions with as-built performance improved over the starting point. By targeting the most sensitive perturbation and reducing the computational burden, the decenter differential WFE method produces the greatest number of lenses with improved as-built performance, with 147 solutions demonstrating as-built WFE < 0.17 waves RMS.

The as-built RMS WFE is shown in Figure 4 for the lens demonstrating the best as-built performance and the average as-built performance for each of the methods.

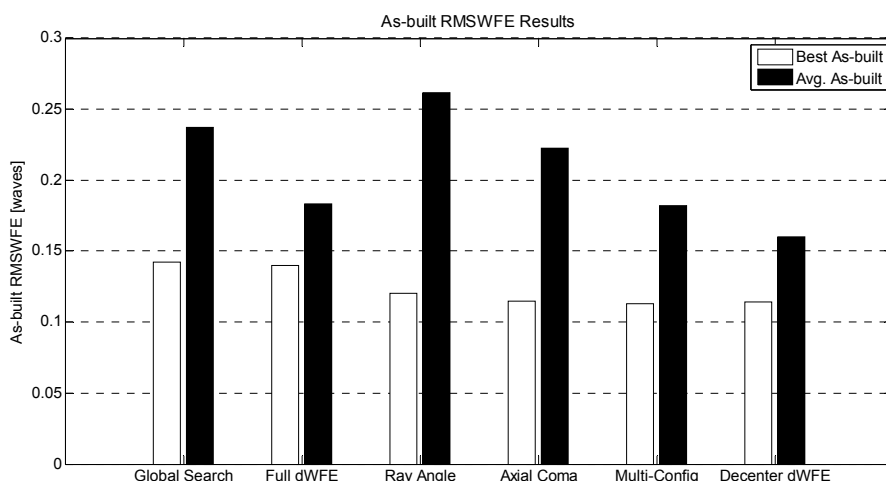


Figure 4. As-built RMS WFE for the lens exhibiting the best as-built performance and the average as-built performance for all methods.

The method using the full integrated differential wavefront error results in an improved average as-built performance over the undirected global search method, but neither finds the lens with the optimal as-built RMS WFE. For the full differential WFE method, this is most likely due to the significantly decreased number of solutions generated in the same time. The ray angle method produces the set of lenses with the worst average as-built performance; to some extent, this is expected. The method relies on identifying a sample ray that is highly correlated to sensitivity, which proved difficult in this highly aspheric design space. The ray angle method is also not intended to produce a large number of good solutions, but to center the solution space around the best solution; it succeeds at this objective. The axial coma, multi-configuration, and decenter dWFE methods all generate the best as-built solutions that are fractionally varied from each other. The decenter dWFE method also produces a solution set with the lowest average as-built RMS WFE.

The designs from each of the methods exhibiting the best as-built performance are shown in Figure 5; several observations should be made concerning these designs. First, note that there is no one particular form that produces the best as-built performance. Second, unlike traditional design forms dominated by spherical surfaces, it is not easy to distinguish a highly sensitive design by observation alone. Finally, because there is so much variation in the form of the elements for the lenses producing similar as-built performance, it is desirable to use a design for manufacture methodology that produces a large set of lenses with improved performance. The set may then be further analyzed against other metrics to further improve cost, manufacturability, or performance.

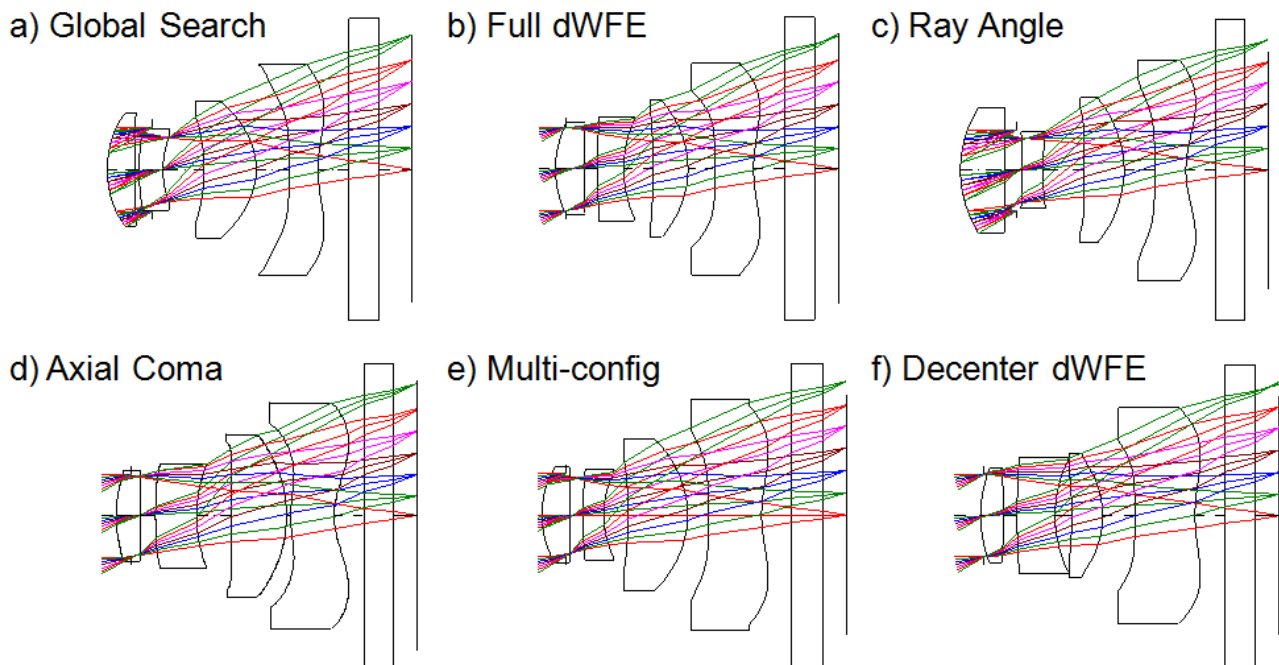


Figure 5. A large variation is seen in the designs exhibiting the best as-built performance from the methods a) global search, b) full dWFE, c) ray angle, d) axial coma, e) multi-configuration, and f) decenter dWFE.

5. CONCLUSIONS

In the high volume miniature camera industry, the as-built performance of a lens significantly impacts production yield and cost. Five design for manufacture methods that were developed for traditional design forms are analyzed for their effectiveness at improving the as-built performance of a highly aspheric camera lens that is common to this industry. A new design for manufacture method was created by analyzing the global solution space for the most sensitive perturbation, constructing a wavefront differential constraint that is highly correlated to that perturbation, and then reducing the ray set used to calculate the constraint for increased speed. The result is a method that produces the largest number of solutions with improved as-built performance, the lowest average as-built RMS WFE, and one of the three designs exhibiting the best as-built performance. For equivalent as-built performance to the base lens starting point, the approach generates a design enabling 1.7X looser tolerances.

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