Meet Your Augmented and Virtual Reality Challenges Head-On: Design Your Next System with Q2D Freeforms in CODE V

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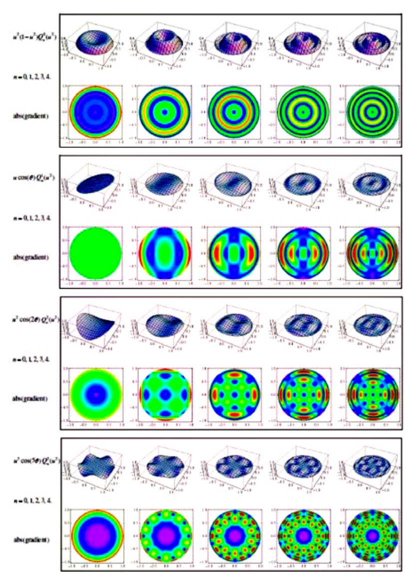
The most challenging optical designs today need sophisticated and precise non-spherical surface shapes. A new surface formulation specified by G.W. Forbes describes a "freeform" surface with orthogonal polynomial deformations (like Zernike polynomials)[1]. This formulation helps provide insight and control over the manufacturability of the surfaces. Other attributes help designers improve optical performance and lower manufacturing costs.

We have developed a new Q2D freeform surface for Synopsys' CODE V® optical design software, based on Forbes' formulation. The surface is available for you under **Lens Data Manger > Surface Type > Q2D Freeform Asphere**. The surface has a best-fit conic base shape and a series of Q-freeform, or *Q2D*, polynomials. X and Y offset terms allow designers to shift the center of the polynomial departure away from the vertex of the base surface. Off-Axis Angle[2] allows easy setup of an off-axis parabola (OAP).



Picture of a few freeform basis functions provided by Forbes in Ref. 1

This freeform surface formulation is a powerful design tool for today's lightweight and compact optical systems. To illustrate its use, we show a non-symmetric, all-reflective design example. The system could serve as a lightweight, compact, head-mounted display (HMD) device for use in augmented reality (AR).

The Augmented and Virtual Reality Revolution Is Well Underway

Augmented and virtual reality (VR) are prominent areas of optics development and research for a range of applications and markets. Some of these include gaming and entertainment, but others include applications in the workplace. A few examples are medical or harsh environment cleanup, as well as simulation and training for challenging tasks. The availability of displays based on low power and OLED technology enables development in AR/VR applications.

All-Reflective AR Device Design Example

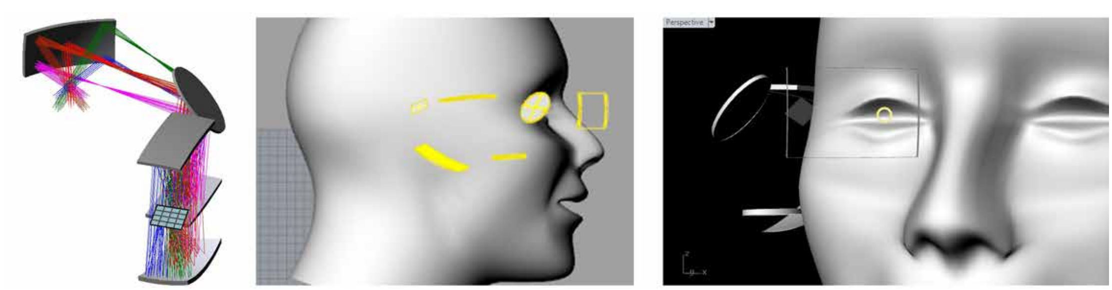
For this example, we created a system based on a commercially available micro-display capable of SXGA resolution and operation at 1280 x 720p. This resolution is satisfactory for many AR applications.

Specifications	Parameter Value
Eye Pupil Boundary ('Eye Box')	7 mm
Eye Pupil (Analysis)	3 mm (average pupil size, well-lit scene)
Detector Size	12.28 mm x 6.91 mm (14.1 mm full diagonal)
Detector Resolution	1280 x 720
Display Pixel Size	9.6 μm x 9.6 μm
MTF for Observation	25 cyc/mm (1/2 Nyquist for display pixels during design) 0.5 cyc/arc min (Nyquist limit for humans)
Luminance	750 cd/m^2 (Lumens/m^2/sr)
Imaging System Focal Length	15.6 mm
Imaging System Focal Ratio	f/2.2 (Full Eye Box), f/5.2 (analysis in viewing direction)
Micro-Display Imager Semi-FOV	24.3^0 (sensor diagonal, ~40^0 H x ~30^0 V Full FOV)

Table 1: Specifications and optical performance metrics

Compact Starting Point Design

The figures below show an initial reflective design to image from the OLED projection micro-display. In the figure at left, you can see the rear surface of the device (a rectangular checkerboard). You also see the optical chain given the pupil position for a wearer's right eye. An all-reflective design is attractive because it is lightweight, compact and free from dispersion-related chromatic aberrations.

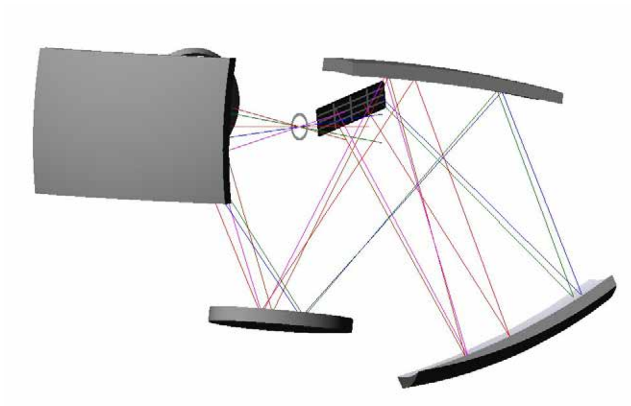


Design side and perspective view relative to adult male head, pupillary distance 64 mm

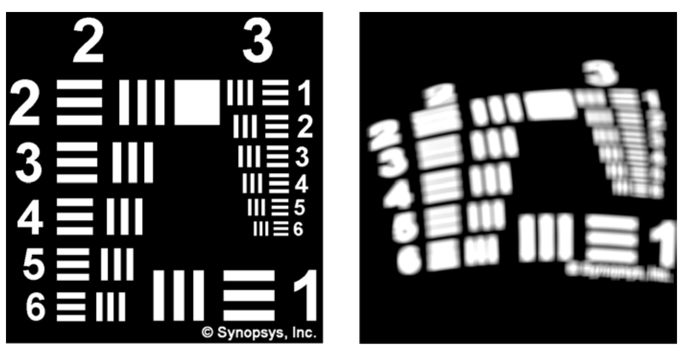
Overview of Design Process

For the example design, we arranged the geometry with the appropriate size and first-order properties. The micro-display semi-diagonal of 7.1 mm sets the image height for the design. This is because we performed the optical design in reverse, with collimated light flowing "out from" the observer's pupil to the optical system. Light reflects from the conic combiner inner surface (a partial reflector since it must transmit the view of the world as well). Then, each of the field points are imaged through the optical chain onto the corresponding position on the micro-display. We will look at the design final performance by reversing the system and consider light projection from the display to the eye as in actual viewing use. For a task like this, optical designers can make use of a very useful system reversal tool in CODE V. The reversal functionality works well in most cases, even with complex, non-rotationally symmetric geometry.

For the initial system layout, we used a constraint-only error function to ensure light reached the proper image plane location within the package required. CODE V offers optical designers the freedom to optimize each system based on optical performance. CODE V also allows a constraint-only optimization to handle packaging and geometric layout considerations. In this case, because the packaging of the system posed a unique challenge, it made sense to optimize for the position and angles of the mirrors first. The mirror packaging constraints were set such that a wrap-around frame could enclose the imaging device along the wearer's cheek.



Initial view from combiner towards the micro-display



Object (left) and Image Simulation (right) for initial geometry. Note poor contrast, high distortion.

Optimization of System Performance with Q2D Freeforms in CODE V

Once we established a starting point design and initial peformance, we next set up the system for optimization. The Q2D freeform surface in CODE V enables the rapid optimization of this type of non-symmetric design. The picture below shows how the freeforms can be set up in CODE V.

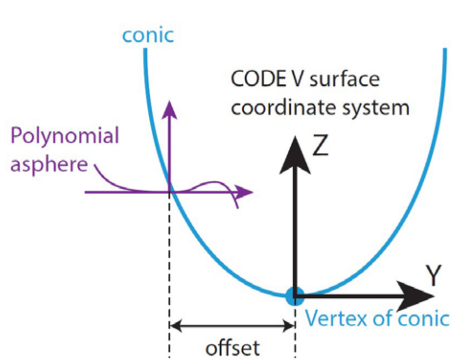
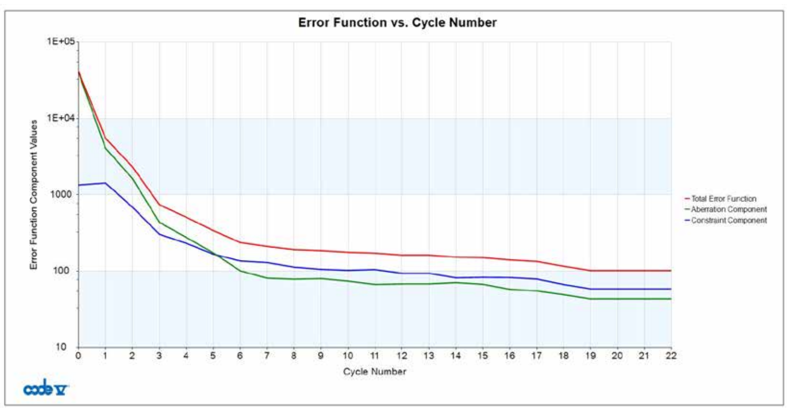


Diagram showing how freeform aspheric terms add to a base conic surface; X offset is also supported.

These freeform aspheric terms can help correct non-rotationally symmetric aberrations in the field of view due to the folded, decentered nature of the system. The designer can apply a position offset in both X and Y relative to the local surface. For this design example, we chose to use three freeform surfaces. The Q2D implementation has radial orders available up to 38^{th} degree for designers to use in their work. In practice, designers should limit the terms to only the orders and orientations needed to meet the requirements of their particular design.

In this example, we allowed the freeform surfaces to have coefficients through the 5th, 8th, and 9th groups (with highest polynomial at 22^{nd} degree). We varied the aspheric departure X, Y location relative to each base conic and held the conic constants near zero. The X, Y offsets were also constrained to small values, resulting in surfaces with reasonable slopes. To achieve an optimized design with good imaging performance, we also allowed the α and β angles of the mirrors (tilts about the local X and Y axes) and their positions relative to the optical axis to vary. We used constraints to match a typical adult male head with pupillary distance of 64 mm. All these terms in addition to the mirror air spaces and curvatures provided a full range of optimization variables for the design.

Using these variables, and considering the packaging constraints, we created an optimization script with the CODE V Macro-PLUS™ programming language. Script-based optimization can be easily combined with graphical user interface (GUI) interactive optimization in CODE V, providing designers with flexibility to work on their projects as they deem most effective for their needs. With the optimization script, we were able to rapidly improve both the imaging and constraint components of the system error function. CODE V offers designers the ability to specify exact constraints that are not included in the error function and are imposed only when needed, or constraints can be weighted relative to the aberration portion of the error function, as their particular project requirements dictate. In the following figure, you can see a plot of the different components of the error function for easy visualization during one stage of the progress of the optical design.



CODE V plot of the total error function (red), aberration component (green), and constraint component (blue) as a function of optimization cycle

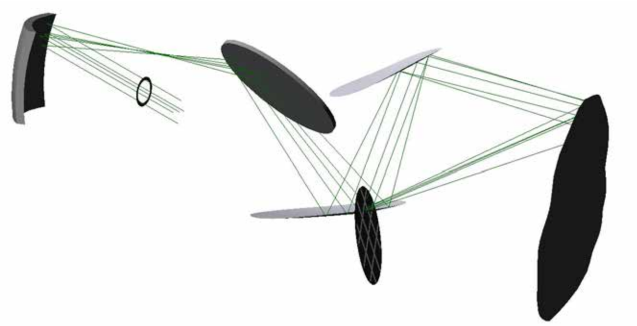
As in any project, engineers must use their judgment to determine when it is appropriate to stop with “computer/paper” design, and when to move on to the finalization of the design for packaging and production. CODE V offers many tools to assist in this work as well, which we describe in the next section.

Optical Diagnostic and Display Tools for System Design

CODE V offers several useful options for viewing, analyzing, and tracking the performance of any type of imaging optical design, including:

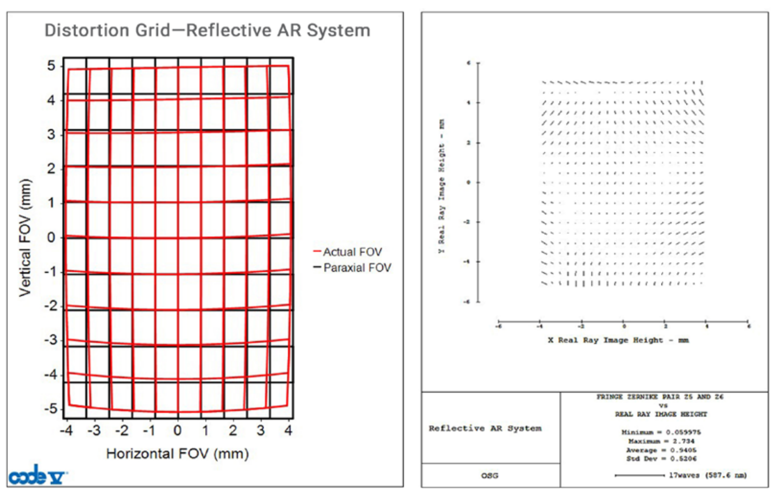
- 3D Viewing
- Distortion Grid Analysis
- Field Map Analysis
- Diffraction Image Simulation
- Footprint Plot
- MTF Analysis
- CAD Export

The 3D views in CODE V give the designer the ability to examine the system in three dimensions. With this information, the designer can set up constraints for requirements of the compact geometry. We used these views to help construct the optimization constraints for the final optical system and optimization.



CODE V's realistic 3D views with rendering controls allow designers to easily manage packaging constraints.

AR systems require reasonable control of distortion—typical specifications may show values under 10%. This level of distortion can be pre-programmed into the display device with the resulting projected image being undistorted for the user. You can see an example disortion grid left-hand figure below.

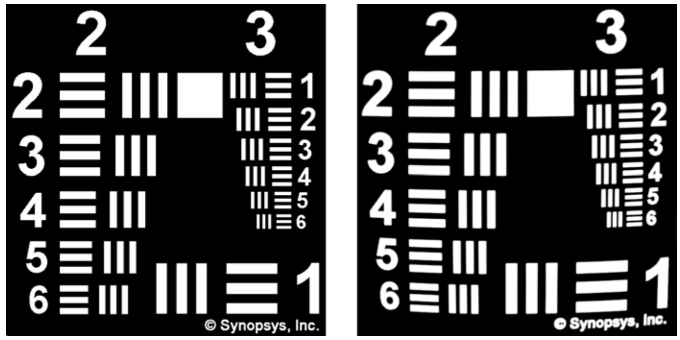


Distortion Grid and Field Map Analysis for AR reflective imaging system

Additionally, CODE V offers Field Map Analysis plots to provide insight into the behavior of the optical system through the entire field of regard. This is especially helpful for non-rotationally symmetric visual systems such as this AR system. Note that nodal aberration theory can help tremendously for improving the performance of such a design[3]. Consider the anti-symmetric nature of the astigmatism Zernike terms shown in the Field Map Analysis plot above. Based on concepts from nodal aberration theory, the designer might build constraints to create a more plane-symmetric behavior for the astigmatism and field curvature (leading to smaller variations in accommodation for the eye, for example).

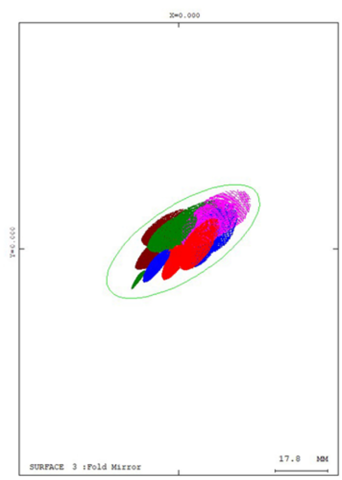
For the purposes of this white paper, we have stopped short of an "ideal" design. As mentioned, we first used a constraints-only error function to achieve a folded path meeting the requirements for the unique packaging. After this, we added the aspheric Q2D surfaces and optimized for reasonable imaging performance. As this is a feasibility-level design, we could also work to reduce sensitivity to alignment and fabrication errors. CODE V provides designers with several effective features for reducing tolerance sensitivity. Primarily, we intend this design to be an example of the use of the Q2D surfaces to solve an interesting packaging challenge for an AR system.

Often, it is useful to show the performance level by simulating the imaging capability for an optical system. CODE V offers an option for diffraction-based image simulation with the capability to create simulations over multiple wavelengths and considering the PSF of the optical system over the entire field of view of the system.



Final 2D diffraction image simulation for example AR design (left: object; right: simulated image)

To aid their work in creating manufacturable, realistic optical systems, designers can use the Footprint Plot option in CODE V to map the beam size and shape on each surface. The numerical and graphical information allows the designer to finalize the proper apertures, including mechanical clearances required for fabrication. The following figure shows one example of a footprint plot (the first fold mirror in the example design). The designer can use the size limits and the origin for the surfaces computed with the footprint option to construct apertures for all the rays with proper clearance, while keeping the geometry as small as possible for a compact design.

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Footprint limits on surface  3
for all field and zoom positions *

    LEFT    -16.189      MM
    RIGHT    27.520
    TOP      21.312
    BOTTOM  -13.792
    RADIUS   32.519

Origin used for ray limits:

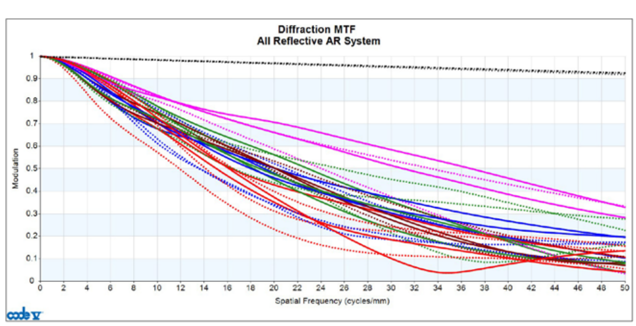
    ORI S3   0.0000       0.0000

Use this origin for minimum ray limit LEFT, RIGHT, TOP, BOTTOM:

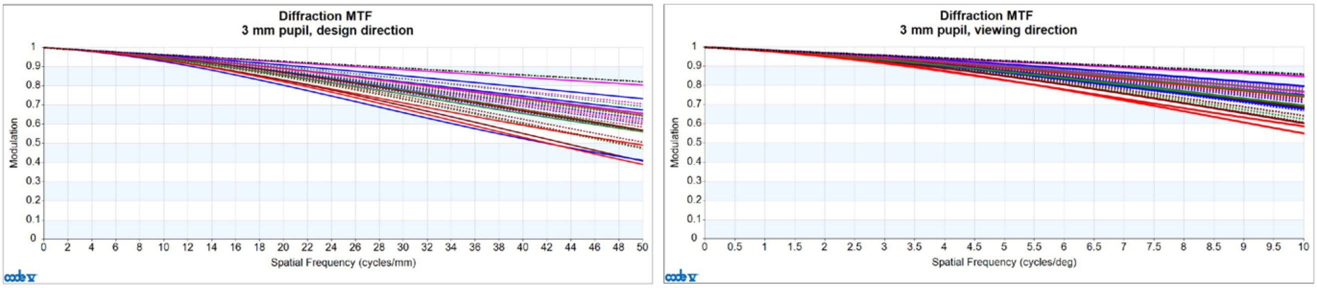
    ORI S3   5.6654       3.7600
```

Footprint analysis with detailed information about ray surface intersections for the optical surfaces

After optimizing the system performance, CODE V offers the designer accurate MTF computations to estimate the performance and simulate the performance relative to normal human visual acuity. The diffraction MTF for the optimized reverse direction design with full 7 mm EPD, as well as the instantaneous pupil MTF for a well-lit image (corresponding to 3 mm eye pupil for the user) are shown in the following figures.



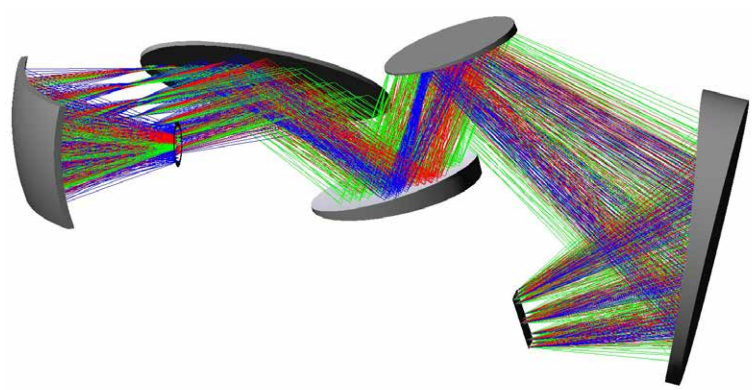
MTF for reverse (design) direction over 7 mm eye pupil diameter



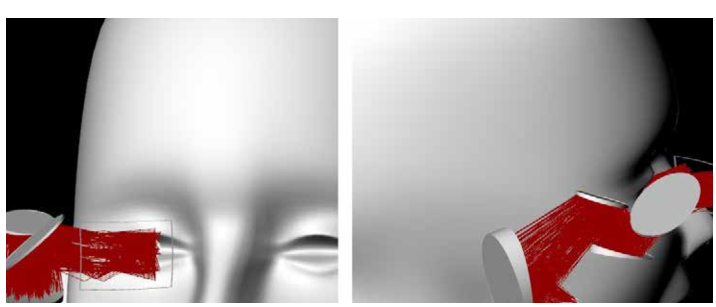
Instantaneous pupil MTF for reverse (design) direction (left) and visual use orientation (right)

The MTF curve at the left in the lower figure shows reasonable resolution at 50 cycles/mm. The MTF curve at the right in the lower figure shows the MTF in the actual visual use direction for the AR device. This MTF curve is plotted to 10 cycles/degree. In practice, most of the eye's resolving power is below about 15 cyc/degree. The normal human MTF is at or below 50% at 10 cycles/degree for most humans, and this is true even more so as age increases through and beyond the middle-age years[4]. The MTF plot for the viewing direction of the design shows performance above 55% for the worst-case field and azimuth at 10 cycles/degree. The optical performance given assumes normal human accommodation for small values of field curvature. In this design, the accommodation values for field curvature were all below 0.2 diopters, and near zero for much of the field of view. They also vary by not more than 0.1 diopter from field point to field point in the example design, which will yield smoothly varying imagery for the viewer.

Finally, to support engineering team project collaboration, CODE V offers a flexible CAD Export feature. The CAD Export enables designers to easily share their optical design layout and ray paths in a variety of formats. This enables early collaboration with mechanical and systems engineers using design software of their choice to ensure a functional full system solution. An example of using CODE V CAD Export for the AR system is shown in the following figures. The first figure shows the CAD rendering of the design, and the second set of figures show the AR optical system design as would be worn for a typical adult male (64 mm pupillary distance was assumed for this user, to provide a relative scale).



3D CAD Export view of final optimized AR system



Final CAD software package front view (left) and side view (right) with nominal adult male wearer

These options and analyses are easy to use and are available for designers in CODE V. In this example, they show the all-reflective AR optical system as a reasonable feasibility-level design, making a good starting point suitable for further study as a projection system for HMD visual optics.

Some Final Tips for Optimization with Freeform Q2D Surfaces in CODE V

Packaging should be considered very early in the design so mechanical constraints don't preclude your optical solution. CODE V has powerful functions to support ray clearance controls during optimization.

Due to the complexity in optimizing this type of system, running local optimization sequences mulitple times can be more successful than running a single optimization. Derivative scaling in CODE V helps to escape deep troughs in error function space in favor of better solutions.

EFL constraints should be managed with ABCD matrix computations (available in CODE V) since paraxial values are generally not valid for folded, tilted, decentered and non-rotationally symmetric systems.

Limit X, Y offsets for freeforms to values giving reasonable slope departure (to aid manufacturability). CODE V provides tools to evaluate and control angles of incidence on each surface during optimization.

Reasonable normalization radius values should be maintained during optimization. The designer can set user-defined constraints to control the ratio of the normalization radius to maximum surface aperture.

Bounding boxes and/or edge apertures are recommended for Q2D surfaces. These limit the regions for ray intersections to minimize stray ray paths during tracing of compact, folded geometries.

Summary

A new freeform surface formulation based on the Forbes Q2D type polynomials is available in CODE V. The Q2D surfaces enable engineers to solve challenging design problems while providing surface shapes more readily manufactured in production optical systems. Using these surfaces, we showed an example optical design for an all-reflective AR imaging device to a feasibility level. We then showed the performance for an instantaneous pupil for realistic visual acuity limits. The example shows the power of CODE V in optimizing optical designs using this new surface type, giving optical engineers another excellent option for solving today's challenging design problems.

References

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