Conformal optical elements offer the promise of enhanced aircraft and missile performance, as well as the potential of improved commercial applications such as microlithography and precision illumination. To turn potential into reality, a number of technical issues must be understood and solved in the areas of optical modeling, optimization, fabrication, and testing.

BY KEVIN P. THOMPSON AND J. MICHAEL RODGERS

CONFORMAL OPTICS:

KEY ISSUES IN A DEVELOPING TECHNOLOGY

Conformal optics is currently a subject of great interest among different user communities.[1] Research efforts, fueled by funding from a substantial Defense Advanced Research Projects Agency (DARPA) program, are now underway to study the design, performance characterization, manufacture, and testing of these elements with the goal of deploying systems using conformal elements within the next decade.

In all defense-related developments today, the challenge is achieving significant gains in performance, under ever-tightening cost containment requirements. For conformal optics programs, the goal is to achieve the capability to design, manufacture, assemble, and install new types of windows and optical systems at a cost far less than the cost savings that can be expected from fuel reduction and range increase. Early research results indicate that this should be possible.

This article reviews the technology that drives conformal optics and discusses several areas of current research.

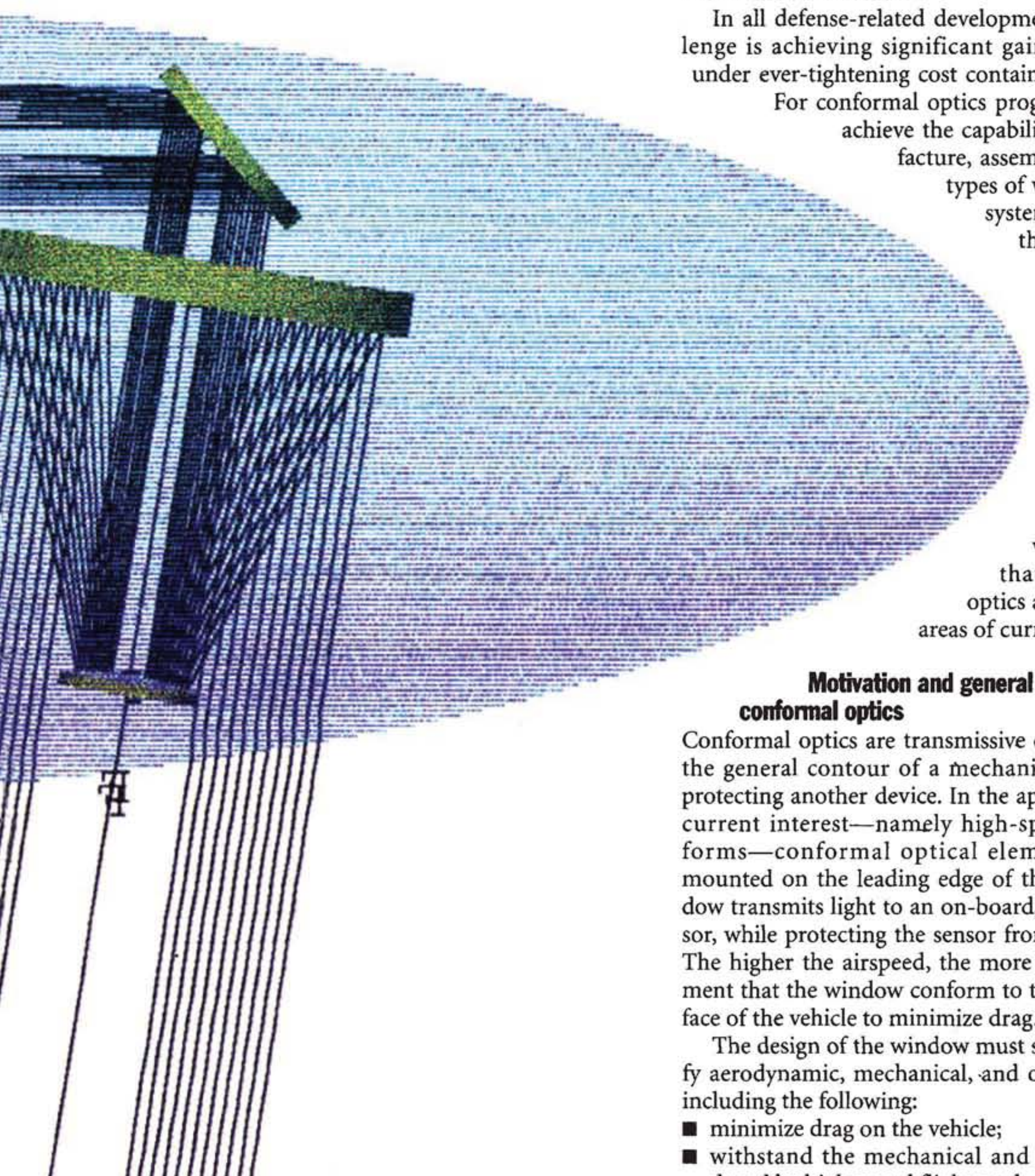

Figure 1. Side view of a conformal missile window with scanning optical system.

Motivation and general requirements for conformal optics

Conformal optics are transmissive elements that follow the general contour of a mechanical structure, often protecting another device. In the application of greatest current interest—namely high-speed airborne platforms—conformal optical elements are windows mounted on the leading edge of the vehicle. The window transmits light to an on-board, electro-optical sensor, while protecting the sensor from air flow and heat. The higher the airspeed, the more critical the requirement that the window conform to the surrounding surface of the vehicle to minimize drag.

The design of the window must simultaneously satisfy aerodynamic, mechanical, and optical requirements including the following:

- minimize drag on the vehicle;
- withstand the mechanical and thermal loads produced by high-speed flight; and

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- minimize optical aberrations and boresight errors of the transmitted light.

Ideally, a conformal surface is a seamless part of the aerodynamically optimized exterior of the vehicle, differing from the surrounding metal/skin only by the fact that it is transmissive. However, limitations in optical design methods and component fabrication techniques have to date prevented the use of conformal shapes. Consequently, while current windows minimize the optical aberrations and boresight errors, they do not minimize drag on the vehicle. The purpose of the current research is to develop windows that can be manufactured with a shape substantially determined by aerodynamic, not optical, considerations.

For the optical design process, the challenge is to determine what family of surface types provide a balance of aerodynamic and optical imaging performance, and to provide the optical designer tools for understanding, visualizing, and optimizing the window shape parameters in conjunction with the optical system that looks through it. The primary challenge for the optical testing process is how to effectively test these new families of surfaces; for the optical manufacturing process, it's how to develop manufacturing methods that allow these new surfaces to be produced cost effectively.

The driving parameters for the optic designs are "field-of-view" and "field-of-regard." Field-of-view is what the sensor sees at any instant in time. Field-of-regard is the total angular region through which the sensor points during its mission. The local shape of the conformal window changes over the field-of-regard, which drives the design challenge.

Funding

Recognizing the potential of conformal optics, DARPA is currently funding two multi-company teams to independently explore the characterization, design, manufacturing, and testing of conformal windows. One team led by Raytheon TI Systems, includes Boeing, the Center for Optics Manufacturing, the University of Rochester, Sinclair Optics, and Rochester Photonics. A second team led by the Optical Sciences Center at the University of Arizona, includes Hughes Missiles and Space Company, Hughes Space and Communication Systems, McDonnell Douglas Aircraft, Optical Research Associates, Hughes Danbury Optical Systems, and Morton Advanced Materials. The deliverable items will include a fabricated conformal window to be used in a demonstration. If the results are successful, deployment of conformal windows can be expected to follow.

The DARPA program will significantly benefit the optics industry. It is supporting key research in optics design technology, modeling of complex surfaces, optical fabrication and testing of complex shapes, and replication of complex geometries. All of these developments in core optics technologies will provide competitive benefits to many optics industries. Asymmetric, aspheric optical surface shapes are useful in other, non-aerodynamic applications, and the tools developed for the aerodynamic applications will be relevant to static applications. Examples include microlithographic relay lenses and precision illumination systems. Thus, conformal optics research will have an impact beyond the industry segment currently most interested in it.

Individual companies are supplementing this funding through their own research efforts in technologies related to conformal optics. Much of this effort is classified or company confidential, but some work has appeared in the open literature. [1–3]

Limitations of current window technology

Airborne platforms require on-board optical targeting and sensing. Currently the ports that these systems look through are either spherical windows (often mounted as an external pod) or faceted arrangements of flat windows attached to the airplane body. These methods are aerodynamically poor because they do not conform to the mechanical structure of the vehicle and thus substantially increase drag.

However, spherical and flat windows are optimal for optical design because they produce aberrations that change little across the field-of-regard. Optical performance is critical in these sensors. Near-diffraction limited wavefront quality and low boresight error is required across the field-of-regard. As a result, the optics design teams have promoted the use of simple window shapes. One outcome of this is that the fabrication, testing, and production manufacturing of the windows has been based on conventional technology.

The goal is to incorporate a new type of window, which supports the necessary field-of-regard and optical performance while reducing drag, decreasing fuel usage, and allowing for higher speeds and greater ranges. The challenge is to expand the capabilities across the industry in order to empower the development of these new windows.

Challenges to existing optics industry tools and processes

Because the equations governing aerodynamic and optical performance are completely different, there is an inherent conflict in designing conformal optical elements. In an aircraft wing, for example, the ideal shape is asymmetric with the local curvatures continuously varying across the surface. In addition, the local curvatures are different in the orthogonal directions, which manifests itself as an astigmatism in the optical system. The optical designer is left with the problem of how to correct the substantial aberrations generated by the conformal shaped window.

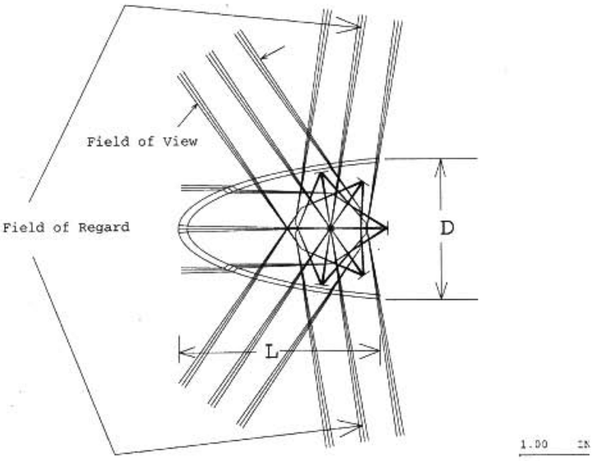
The fabrication and testing challenges are associated with the new surface geometries. These shapes are not rotationally symmetric, and may not even be off-axis sections of rotationally symmetric aspheres. In addition to the unusual shapes, the departures of the surfaces from spheres or even conic sections can be substantial, exceeding an inch!

The following describes in greater detail the ways these challenges are being addressed in different aspects of the technology.

Optical design considerations

Windows used to date are either flat or spherical. These window shapes degrade the aerodynamic performance for the highest speed vehicles. However, the optical aberrations they generate, while large, are of a type that can be adequately compensated for in the imaging optics that follow the window. In the newest window shapes now being investigated, the window surface shape is based on reducing the aerodynamic effects. These surface shapes are developed in mechanical CAD modeling and design environments. The design tools model surfaces as facets distributed over a fine mesh, rather than as continuous surface shapes used in optical design.

The first challenge for the optical designer is to develop an optically useful surface description. The aerodynamic optimization of the surface does not require that the surface be defined to submicron precision. As a result, a relatively coarse mesh optimization is entirely adequate and is used by the airframe designer. The resulting surface is too ambiguous to be used directly in an optical design environment. Therefore, the first task is to develop an adequate representation of the



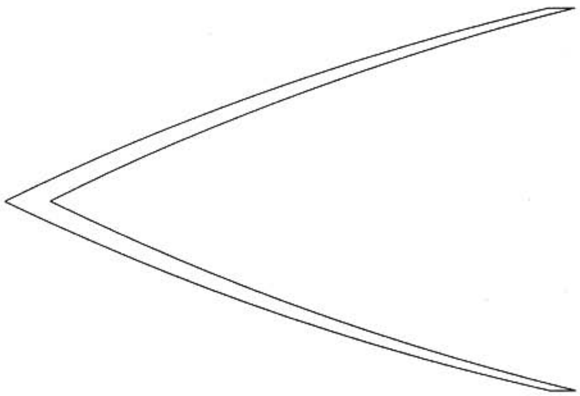


Figure 2. (Left) Illustration of key parameters in missile window: Field-of-view, field-of-regard, and L/D ratio.

Figure 3. (Right) Ogive shaped missile window.

surface for optical ray tracing. This can be done using either analytic surface type fits within the envelope of ambiguity or by developing closer mesh spline representations of the surfaces. To enhance communication with the airframe designer, many optics design packages now accept initial graphics exchanges specification (IGES) and standard for the exchange of product model data (STEP) transferred surface definitions.

While ray trace programs can work equally well with spline or analytic surface definitions, optics designers prefer analytic surfaces. This is because the analytic surface equations and their coefficients often give insight into an optical design strategy that may improve imaging performance. As a result, there has been a dramatic increase in the number of types of analytic surface shapes that optics design programs can model. It is now common for design programs to provide over 20 analytic surface types and an interface for quickly experimenting with new surface types.

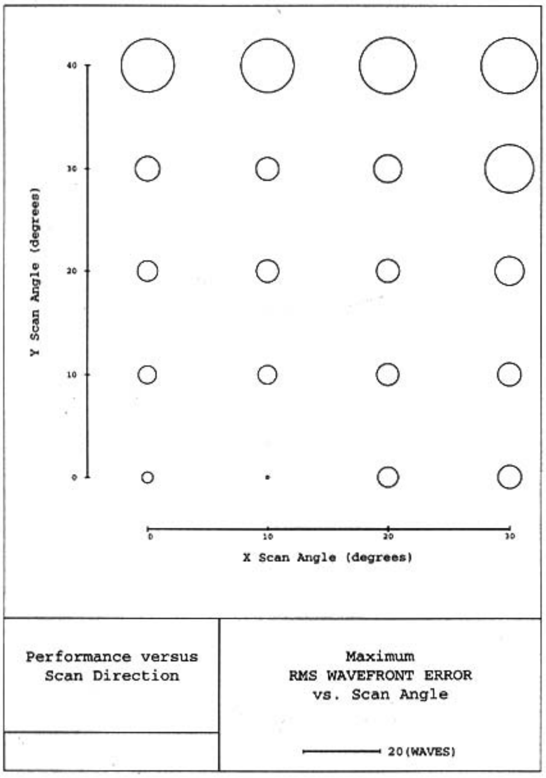
Historically, optical design has been based on aberration theories that assume the optical system is rotationally symmetric. When faced with optimizing an optical system without symmetry, one approach has been to simply add more sample points to the optimization merit function and rely on computer algorithms to provide an "optimal" solution. While computer based optical system optimization technology is rapidly advancing, it still requires user intervention to be consistently successful. To aid the user in interpreting the state of the optics design, more effective tools are needed to display the performance of nonsymmetric optical systems.

In the case of the conformal window system, there is one very important feature that makes the effective extension of the optical design tools practical. Most imaging optical systems that follow the window have circular or nearly circular aperture stops. As a result, there are no new types of optical system aberrations in a device viewing through a conformal window. The only change is the dependence of each aberration type (*e.g.* spherical aberration, coma, astigmatism) on the field-of-view; the field-of-regard is no longer rotationally symmetric. This fact can be leveraged by providing the optical designer with a new display of the magnitude and orientation of both composite measures of image quality and individual aberration terms over the field-of-view. With a complete field visualization, the optical designer can use his accumulated insight into methods of aberration correction to develop optical design strategies for conformal window systems.

The asymmetric and aspheric shape of fully conformal windows introduces conventional types of aberrations, impossible to completely correct with rotationally symmetric sensor optical elements. Furthermore, as the sensor is pointed through its field-of-regard, the field-of-view samples different portions of the conformal window with a continuously varying shape. As a result, the aberration mix changes with field-of-regard. Aberration correction by the sensor optics must be done by use of one or more of the following techniques to provide correction throughout the field-of-regard:

- cylindrical or toroidal elements;
- tilted and/or decentered elements;
- anamorphic aspheric surfaces;
- diffractive optical surfaces; or
- auxiliary elements.

With the enhanced set of optical surface definition methods, the improved database communication with airframe designers, and with the new tools for displaying the optical system aberrations over the field-of-view and the field-of-regard, exciting progress is being made in developing new families of optical systems. A key to this progress has been that the systems are based on circular or near circular aperture stops, allowing optical designers to use their insight into the design of flat or spherical window optical systems in developing high performance designs that look through conformal windows.



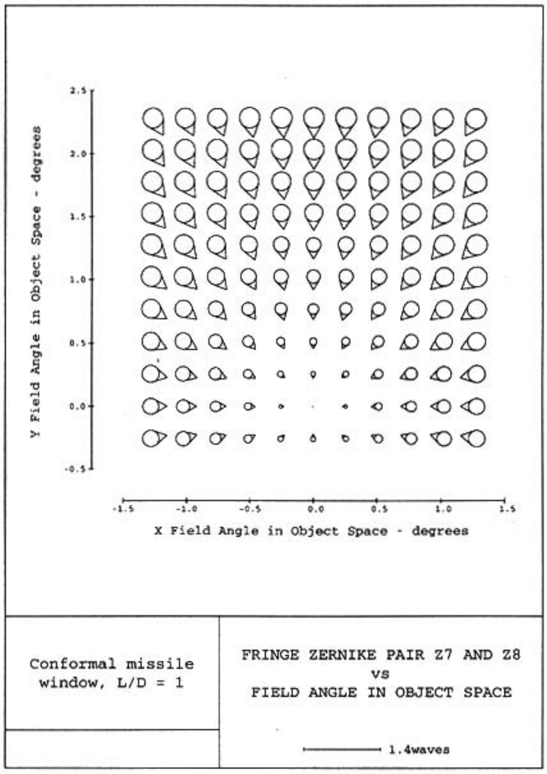


Figure 4. (Left) Plot of maximum RMS wavefront error over field-of-regard (performance symmetric about the lines $X = 0$ and $Y = 0$).

Figure 5. (Right) Plot of Zernike 3rd order coma over one instantaneous field-of-view.

Fabrication and testing challenges

Conformal window shape manufacturability is a key factor in the optical design process. Here, manufacturability is really defined by production cost. Almost any near aerodynamic shape can be fabricated, but it is often at a very high cost. The challenge for the fabrication process is to then develop cost-effective polishing and testing methods and/or development of replication processes for materials that are useful for window applications. In the near term, the area being driven to new levels of performance is the testing and characterization of nonsymmetric, aspheric surfaces having large deviations from the beset fitting sphere. Again the challenge isn't so much in developing a method for doing it once, but to develop a robust technology that can be agilely adapted as the program and surface complexities evolve.

In practice

Figure 1 (see page 24) shows an example of a missile window as it interfaces with the missile body. A key parameter for such windows is the "L/D" or fineness ratio (*i.e.*, the ratio of the length to the diameter, as illustrated in Figure 2, with the focus optics modeled as a zero-thickness perfect lens element). For spherical windows, the maximum L/D is 0.5 (a hemisphere). Aerodynamic analysis shows that drag can be substantially reduced and thus range increased when the fineness ratio is increased to 1.0 or more. Only a conic or other asphere can achieve a ratio greater than 0.5.

This example demonstrates at the simplest level the tradeoff involved in design. Aerodynamically, the ideal shape is a type of ogive, which is formed by rotating an axially symmetric surface about an axis displaced from the original surface's axis of symmetry. This results in a surface with a sharp point, where the slope is discontinuous (see Fig. 3). Such a shape produces aberrations that are uncorrectable by practical optics. An alternative to the ogive ideal is an ellipsoidal outer surface, where the local radius of curvature is highest at the nose, but not infinitely high as in the case of an ogive. The optical design tradeoff is between families of curves that optimize optical and aerodynamic considerations. As expected, the best optical performance occurs when the nose has the roundest possible shape.

To compensate for the aberrations of this surface, the inner surface and subsequent elements must be appropriately designed. Typically, the inner surface will echo the aspheric shape of the outer surface so that the transmitted wavefront error across the field-of-regard is minimized. Subsequent optics, whose locations may change with scan angle, correct for residual aberrations.

The performance of the optical system can be characterized by full field displays of aberrations across the field-of-view and field-of-regard. Figure 4 shows the maximum root mean square (RMS) wavefront error in any field-of-view across the field-of-regard. Figure 5 shows a plot of the Zernike 3rd order coma term across the field-of-view, centered 1° off the window axis.

At the 1997 OSA Annual Meeting, there will be a series of papers from members of the two teams currently working under DARPA funding. Some examples of the more complex asymmetric window geometry designs will be presented at that forum.

Materials and coating issues

Critical issues in the selection of materials for infrared conformal windows include hardness, resistance to rain, solid particles, and thermal shock, transmission in the desired infrared band (*e.g.*, 3–5 or 8–12 µm), and change in refractive index with temperature.

The literature[1] identifies various window material candidates for short and long infrared spectral bands. For the 3–5 µm band, sapphire is a good window material due to its strength and chemical stability. Its disadvantage as a conformal window is that its hardness makes it difficult to mold. In the 8–12 µm region, leading candidates are zinc sulfide, germanium, and silicon. Chemical vapor deposited diamond can be used as a window material in the 8–14 µm band and as a thin protective coating in the 3–5 µm band.

Antireflective and protective coating issues are significant. The windows are directly in contact with high-speed air and are thus subject to damage by water, dust, and other elements. If the coating cannot withstand this environment or does not adequately protect the window, then the expensive window must be removed for recoating or even repolishing. This is a significant cost issue for aspheric conformal windows.

Thermo-optical effects

The high velocity airflow across the window surface increases temperature and sets up asymmetric thermal gradients in the window material. The thermal gradients change the index of refraction via the coefficient of change of index with temperature (dn/dT), change the shape of the material via the coefficient of thermal expansion (alpha), and contribute to change in refractive index due to internal stress. The distribution and magnitudes of the thermal gradients change rapidly with time—especially on flyout. Precise modeling of realistic thermo-optical effects is one of the most difficult tasks in conformal window analysis, requiring considerable computer resource and interpretive talent. As these advanced designs mature, the ability to reduce analysis time while improving model fidelity will become an important factor in the design process.

Other applications

Although aerodynamic systems are the main focus of current conformal optics work, other important non-aerodynamic technologies can benefit from the design and fabrication tools developed for airborne vehicle windows.

One example is the design of optical microlithographic systems. As feature sizes drop below 0.35 µm, to an ultimate goal of 0.1 µm or smaller, low wavelength radiation such as extreme UV (10-nm class) must be used. No transmissive material is practical for these wavelengths, so systems consisting of tilted aspheric mirrors are used. Unusually shaped aspheric surfaces, not merely sections of rotationally symmetric surfaces, may need to be used to achieve the estimated 1 nm-class distortion required for these features. Tools developed to design, characterize, and fabricate the unusual aspherics of missile and aircraft windows can be directly applied to lithographic mirror designs.

Another potential application is precision illumination such as automobile headlights and taillights. A look at any parking lot will reveal that modern cars do not use the old-style round headlights. Swept-back, 'conformal' headlights are the new style. These surfaces perturb the light more severely than the old style and therefore compensating surfaces must be designed on the inside of the window or in the reflector.

Conclusion

The successful implementation of conformal optical elements will require successful engineering efforts in a range of disciplines. Research efforts have made significant progress in enough areas that a prototype conformal system is planned to be demonstrated within a decade.

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Kevin P. Thompson is director of engineering at Optical Research Associates, Westborough, Mass. J. Michael Rodgers is the staff systems engineer at Optical Research Associates, Pasadena, Calif.