Packaging Optical Systems

by Ken Sauter

Sauter Industrial Design

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I have to say up front that I don't design optics, nor am I an optical expert, nor do I know everything there is to know about the mechanical side of optical systems. What I do know, though, is how to mount lenses and optical elements so as to make an optical prescription work as intended. It is not necessary to know all about optics to do a good job of packaging an optical system. It is necessary, however, to understand what is important and must be dealt with. This article is addressed to mechanical designers who are relatively unfamiliar with optics.

About optics

Optics are very unforgiving. When packaging optical systems, it is frequently necessary to hold tolerances of .0001-.0002 inch, although tolerances in the .001-.003 inch range are much more common.. Lens trains cannot bend or twist in use. Since optical systems require such tight tolerances, machined parts are usually used to mount optical elements. Even with machined parts, though, It is usually not possible to maintain tolerances of .0001-.0002 inch in production at a reasonable cost, so it's necessary to rely on other methods of setting and maintaining those tight tolerances. Molded plastic offers the benefit of consistency from part to part, and can usually hold a tolerance of .001-.002 inch from part to part. With plastics, however, it's usually necessary to do some production tuning to get the plastic to repeatedly hold lenses in the proper location.

Unless the system you are designing is incredibly simple or has low performance, it will be necessary to make precise adjustments in every production system to make the prescription work. Production testing is a regular part of building optical systems. One of the difficulties in adjusting systems is that the adjustment has to be locked in place once it's made. Turning the jam nut or whatever part is used to lock the adjustment usually readjusts the adjustment, so you have to do some back and forth to get the adjustment to hold in the proper location. Your production people should be familiar with this phenomenon and know how to deal with it. Designing a way of fixing an adjustment without changing it is the best solution.

Optical elements are usually round with spherical surfaces, but come in all shapes and sizes. You may have to mount prisms, square windows, cylindrical lenses, pellicles, or some weird shape. The important thing to remember is that every optical element must be precisely held in place for the life of the product.

You may have to package two or more prescriptions for a given device. For instance, you may have an objective prescription to create an image, then have an eyepiece prescription in order to focus the image on the viewer's eye. If you're dealing with light of different wavelengths going to different parts of your system, you may have a beamsplitter and a different prescription for each wavelength. Filters and coatings may be used to control which wavelengths of light get to different parts of the system. Another thing to remember is not to stress optical elements. Unlike many things that get retained or screwed down, optical elements cannot handle much stress without damaging optical performance. Just tightening a lens retainer too much can make optical performance unacceptable. Ideally, you will mount all of your optical elements so they are held solidly in place with no stress. That allows the prescription to perform as intended.

What makes up an optical system?

Every optical system starts with a prescription. A prescription begins with optical requirements established by the ultimate customer for the device. It will assume a certain object size, distance from the viewer, resolution of the image, and other optical requirements. It will include clear aperture diameters, lens thicknesses, lens radii, as well as any unusual optical forms used. The prescription, or the optical designer, should provide you with the mechanical tolerances necessary to make the prescription work. You will have to sit down with the optical designer who generated the prescription to find out exactly what the prescription requires. Prescriptions seldom make things easy to understand or provide all the information you need, yet you must know all relevant information to design the system properly. Something optical designers can forget is the annular ring you will need to mount the lenses. They are concerned about making the optics work, but you have to physically mount it, so you need to tell them how much diameter beyond the clear aperture you need to provide a mounting surface and a place for a retainer to hold the lens.

The systems I have worked with usually have an objective, which is the foremost lens assembly on the system. This is the lens that gathers the light and forms an

Understanding Optical terminology

These are some of the terms you will deal with when packaging optical systems. There is also a very good, but incomplete, glossary of optical terms at www.photonics.com.

Annular ring: the area outside the clear aperture that is used to mechanically mount the lens or element.

Asphere: A lens element in which at least one face is non-spherical and defined by conic sections revolved around the lens axis.

Center thickness: the thickness of a lens or element along the optical path measured at the optical center of the element.

Clear aperture: the area in the center of an optical element within which light rays pass through or are reflected from the element and which must be kept clear of obstructions.

Doublet: A compound lens consisting of two elements, usually cemented together on a common surface where each lens has the same radius of curvature.

Element: any member of an optical train that bends or transmits light.

Lens: An optical component consisting of one or more pieces of optical glass with surfaces curved so as to cause the transmitted rays from an object to converge or diverge, thus forming a real or virtual image of that object.

Lens Train: an optical train made up of lenses.

Optical train: a series of adjacent optical elements designed to bend or straighten light rays in a certain way for a certain purpose, usually to create an image at a particular location.

Power: the ability of a lens to bend light. Higher power bends light more, lower power bends light less. The combination of radius of curvature and glass index determine the power of a lens.

Prescription: a list of optical element descriptions, given in a particular order, giving radius of curvature, air spaces between lenses, clear apertures, and glass types, given surface by surface. A prescription is the fundamental definition of an optical system. Frequently difficult to understand.

Prism: An optical element having at least two polished plane faces at an angle to each other, from which light is reflected or through which light is refracted.

Radius of curvature: the curvature, usually spherical, on the surface of an optical element, which, combined with the radius of curvature on the opposite side of the element, that defines its shape.

Refraction: The bending of incident light rays as they pass from one optical medium to another having a different refractive index.

Refractive Index (Index of Refraction, Glass Index, or just Index): The ratio of the velocity of light in a vacuum to the velocity of light in a refractive material for a given wavelength.

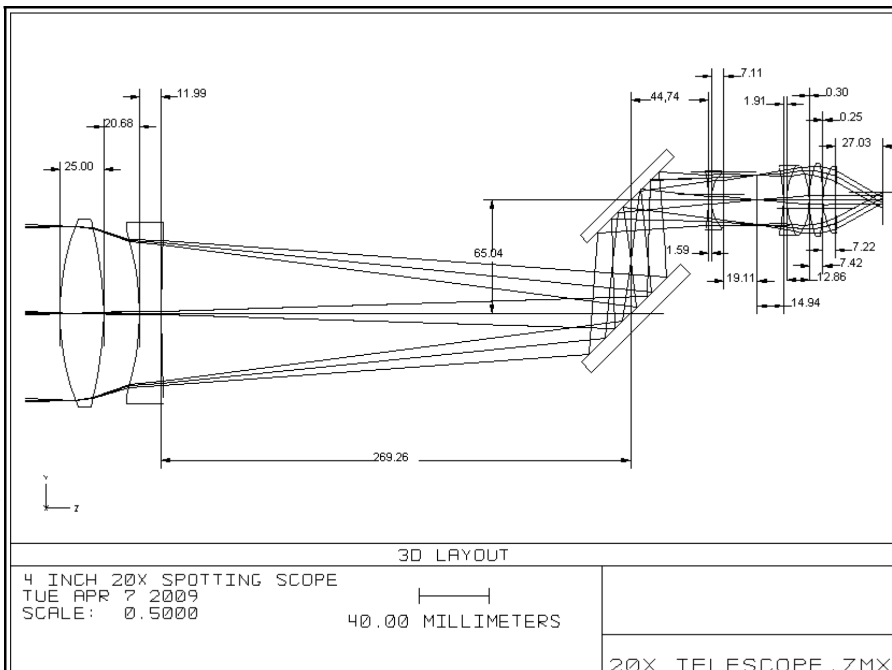
Reticle: a network of lines or wires on an image plane that the eyepiece of the optical system focuses on. Usually used for aiming or measuring, and usually adjustable.

image inside the system. They also usually have an eyepiece, which looks at the image and allows the user to focus on it. Eyepiece focus adjustments are measured in diopters, which correspond to an axial movement of the eyepiece. The optical designer will determine what those adjustments need to be. The objective also usually has a focus mechanism so the image can be precisely focused on the reticle or image plane.

An optical system could have any number of other elements, depending on its purpose. Prisms, Collimators, filters, windows, image tubes, light sources, all have a purpose in some system. It may be a simple magnifier or a complete observation system with laser range finders and digital imaging, or it may be a huge astronomical telescope. Every system has its own peculiar requirements.

Understanding a Prescription

Since every optical design begins with a prescription, you'll have to learn to understand them, at least enough to package the design properly. A prescription lists a lot of information about an optical design, but the part you really need to understand is the Surface Data Summary, which lists each surface of the prescription in consecutive order, from where the light enters the system to where the image is. This is what you are designing around. The convention is that light enters from the left and exits at the right, but there are exceptions. You will need a ray trace to make sense of it all.



Adding dimensions to a ray trace. This is one way to verify that your 2D data matches the prescription.

Remember that optical systems can be designed for any optical purpose and can vary wildly from one job to the next. You will have to study each prescription carefully, as well as talk to the optical designer, to understand the purpose of the system. We will deal here with a relatively simple prescription in order to get a handle on some basic principles. You read the prescription from top to bottom and left to right. The thickness and glass type apply to the area between the surface on the line they are on and the next surface below. You will quickly realize that prescriptions are not intended to be easy for mechanical designers to understand.

If you compare the surface data summary below with the ray trace shown above, you can compare the two to understand exactly which radius goes with which lens and on what side. One of the first things you will notice is some dummy surfaces the optical designer uses that you don't care about. In this case, surfaces 1, 8, 9, 10, 11, 25, 26, 27, and IMA are dummy surfaces. You can't ignore the airspaces connected to the dummy surfaces, though. The air spaces are part of the prescription. Compare the prescription to the ray trace to determine which are dummy surfaces and ignore them. Since the convention is that light enters from the left, a positive radius indicates a surface with the radius center to the right of the surface. A negative radius indicates a surface with the radius center to the left of the surface. A negative thickness indicates a reflection from a mirror. A reflection from a second mirror will change the sign and indicate a positive thickness. A radius of infinity indicates a flat surface.

Surface Data Summary

Surf	Type	Radius	Thickness	Glass	Diameter	Conic	Comment
OBJ	STANDARD	Infinity	Infinity		0	0	
1	STANDARD	Infinity	20		0	0	
STO	STANDARD	144.52	25	BK7	108	0	
3	STANDARD	-208.48	20.64		108	0	
4	STANDARD	-150.28	12	F2	94	0	
5	STANDARD	938.05	269.26		104	0	
6	COORDBRK	-	0				
7	STANDARD	Infinity	0	MIRROR			
8	COORDBRK	-	-30				
9	STANDARD	Infinity	-5		0	0	
10	STANDARD	Infinity	-30		0	0	
11	COORDBRK	-	0		-	-	
12	STANDARD	Infinity	0	MIRROR	70	0	
13	COORDBRK	-	44.65		-	-	
14	STANDARD	-77.09	1.6	620603	34	0	A
15	STANDARD	24.79	7.19	720293	32	0	B
16	STANDARD	Infinity	19.13		32	0	
17	STANDARD	Infinity	14.91		34.55	0	field stop
18	STANDARD	-79.61	1.85	720293	38	0	
19	STANDARD	40.13	12.9	620603	40	0	
20	STANDARD	-40.13	0.18		40	0	
21	STANDARD	63.53	7.49	620603	42	0	
22	STANDARD	-149.48	0.18		42	0	
23	STANDARD	37.47	7.24	620603	38	0	
24	STANDARD	334.4	27.06		36	0	
25	STANDARD	Infinity	1.12		13.18	0	eyepoint
26	STANDARD	Infinity	100		14.76	0	
27	STANDARD	Infinity	0		156.46	0	
IMA	STANDARD	Infinity			156.46	0	

One lens. Two radii, one thickness (25), glass type, and diameter.

The first lens in this prescription is circled. It has a center thickness of 25mm, a first convex radius of 144.52mm, and a second convex radius of 208.48mm. Note the sign of each radius. If the signs were reversed, it would be a double concave lens. The distance between the mirrors in this prescription is 65mm. You ignore dummy surfaces 8, 9,10, and 11, but you must add the airspaces to get the distance between surface 7 and surface 12. Looking at the ray trace clarifies what is happening.

I added dimensions to the ray trace to verify that it was accurate. In this case, some of the dimensions were accurate, others were slightly off. This is the reason that you must use the prescription itself as the defining document of the system. CAD data is usually accurate, but with the unforgiving nature of light, you can't afford to be wrong. You must verify and correct your CAD data so it perfectly corresponds with the prescription.

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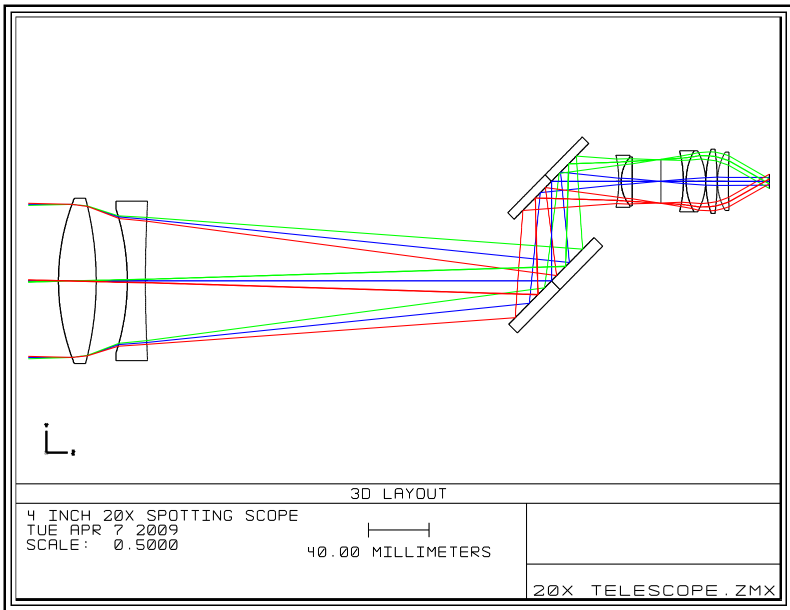
Issues in designing optical systems

In any optical system you will have to mount lenses. Usually the simplest and best way to mount lenses is to put them into a closely toleranced bore on a lens seat and retain them with a threaded retainer. The lens seat must be located so as to put the lens exactly where the prescription requires it to be. Lens locations must also be calculated to create the correct airspace between them, since the airspace is part of the lens prescription. You are essentially recreating the prescription with physical parts. Spacers are frequently necessary to maintain air spaces between lenses. You may occasionally have a prescription that requires a lens to be decentered—i.e., moved sideways—in order to ensure the required optical performance. In that case, you have to allow the lens to decenter without allowing it to tilt. Then you have to allow for potting it in place. Since glass is brittle and subject to cracking and chipping, it is not a good idea to have sharp pieces of metal contacting lenses, such as setscrews, particularly in systems that undergo repeated shock and vibration. If a lens gets chipped or cracked and the defect shows up within the clear aperture, it must be replaced. You want to avoid replacing lenses in a built-up system. It is time-consuming and frequently messy. Nor is it a good idea to have lenses mounted against a sharp edge. I have seen at least one instance where simply tightening the retainer literally sheared the lens at the lens seat because of a sharp-edged lens seat. Putting a slight radius on every lens seat makes it less likely to damage the glass, as well as reducing debris from chipped edges..



A Ray Trace from Zemax. This is a 2D representation of the prescription. You can make a dxf from this and use it to create the lenses.

Keep in mind that wherever you mount the lenses, the image plane has to end up precisely where the prescription requires it to be, usually within a few thousandths of an inch. You'll have to do a lot of top-level layout work to make sure that happens. You don't want to prototype your system and find out the image plane isn't where it's supposed to be. Jury-rigging a supposedly finished design can be embarrassing. Go back to your top-level layout frequently, especially after significant changes, and make certain the image plane is precisely where it should be. Every minute you spend checking that top-level layout is worth it. You may not have to change much because of it, but those changes will be critical. If you don't check for them and make them, you will have problems.

The optical designer should give you a ray trace of the entire prescription, along with the clear aperture of each optical surface in it. Every lens seat must be larger than the clear aperture of the surface it mounts, and no part of the system can be inside the ray traces made at the clear aperture, or the image will be obstructed. Lens retainers must also stay outside the clear aperture.

In any system with an eyepiece it will be necessary to allow for focusing to correct for different degrees of nearsightedness or farsightedness in the user. You may also have to focus the objective to adjust the image plane's location. The optical designer will have to tell you if the focusing lenses can rotate or if they must move without rotating. It makes a difference in how you design the focus mechanism.

In all except rare cases, you will have to seal the system. Foreign matter inside the system will obstruct the image, whether it be gas, liquid, or solid. O-rings will usually do the job, but sometimes you'll have to create some odd seals. For military equipment, this is a critical requirement, and you may also have an immersion or altitude requirement to deal with. Keep in mind that external pressure isn't the only possible problem. Internal pressure at altitude can also cause problems. Be aware of what will happen to your system if internal pressure gets significant. Also be aware of the chemical environment. If your customer uses a cleaning chemical that degrades o-ring material, you'll have a problem.

If sealing is important, it will be necessary to purge the system before finally sealing it. You will need a purge port somewhere on your system that allows you to pull a vacuum or pump air or nitrogen through the system. This requires a pathway for the gas going past lenses and spacers and whatever other elements might be blocking air passage through the system. You may have to add grooves and holes to spacers, grooves through lens seats, or other features to allow gas to flow past optical elements. Once the system is purged, you will need to install a plug in the purge port to maintain the seal. A seal screw with an attached o-ring usually works well for this.

Alignment mechanisms

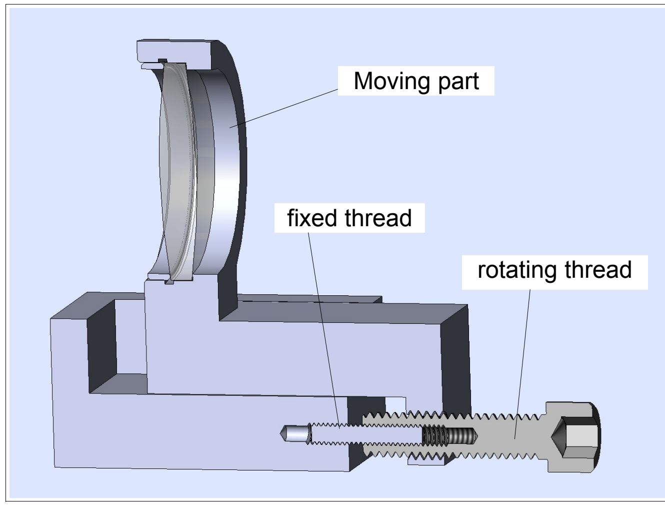
Ideally, you will assemble the lenses into your design, securely retain them, seal the system, and it will work as advertised. That seldom happens the first time you do it. Since you'll have to align your system somehow, here are some possible ways to do it. In all cases, once your adjustment is made, it can't move any more for the life of the system, except for maintenance or repairs.

double eccentric. A double eccentric allows you to decenter an image within a predefined adjustment circle. The difficulty with a double eccentric is that tolerances on the parts can make it impossible to get the image on dead center. In that case, you may have some systems that can't be aligned. Double eccentrics are used in production systems with good success, though.

risley prisms. These are two wedge-shaped pieces of glass that are rotated independently in order to steer the image. It is possible to get the image on dead center as well as steer it within a given angle defined by the wedge.

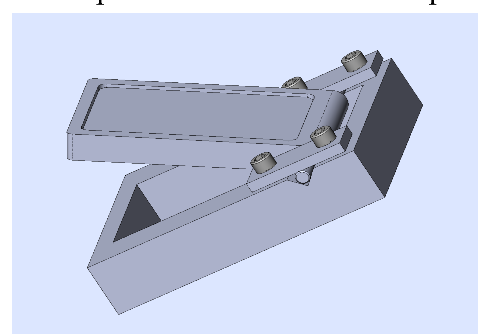
x-y stage. This is a little more difficult to design than a double eccentric or risley prism, but you can get some precise adjustments with it. You'll have some amount of cantilevered weight that may cause you difficulty. Remember, glass is heavy. Purchased x-y stages tend to be very large and impractical for use in a production system.

Dynamic adjustments to the system
You may have a requirement for certain elements in your system to be rotated, moved, or flipped after the system is built. Again, you must remember that any movement outside the prescription parameters will degrade the optical performance of the system. Movement of any element must be precisely controlled. You will frequently need a spring to eliminate backlash, which must always be considered when moving optical components.



Differential Threads. Good for small, controlled movements

Differential threads. Differential threads are created by putting one screw inside another. When one screw is turned, the part moves a distance defined by the larger thread pitch minus the smaller thread pitch. For instance, a 1/32” pitch thread turned against a 1/48” pitch thread will move the element 1/32 (.03125) – 1/48 (.028333) = .0104” per turn. You can create almost any amount of movement you want with differential threads, and it is generally fairly simple to lock the element in place. This is cheap and very effective for small movements.


V-Groove pivot. Allows optically controlled rotation.

Four-bar linkages. Four-bar linkages are quite useful and show up everywhere. The difficulty in an optical system is that the movement must be precise. Cylindrical fit tolerances at the linkage pivots usually aren't tight enough to maintain prescription spacing. You may use a linkage to move or rotate an element to different locations. The linkage must be designed so that when the moving element reaches a particular location it is precisely where it should be. You may have to use a spring or some over-center lock to hold it in a particular position. Remember not to stress the lenses.

Pivots. For rotating elements, pivots must be mounted on conical bearings or balls to make the movement precise. Tightening a plate against a shaft in a V-groove also works. Use the fundamental shape and design of the pivot to keep the element in place rather than part tolerances. Tight tolerances are expensive.

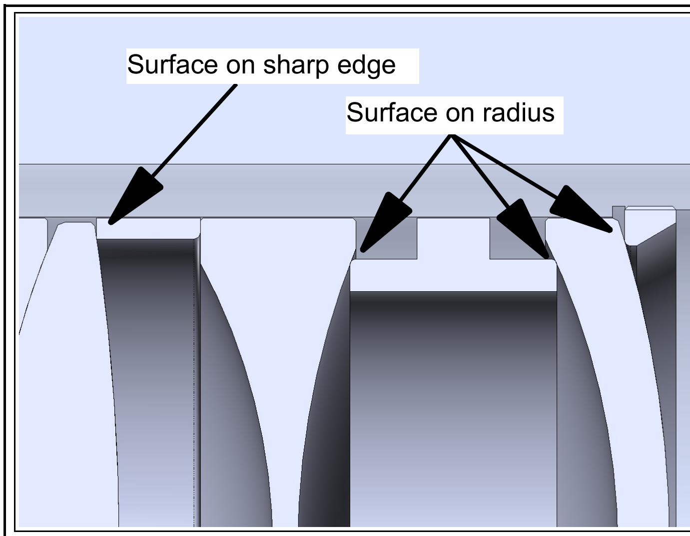
Focus mechanisms. Threaded lens barrels with a jam nut usually suffice for a focus mechanism. You can also use slots and pins, levers, cams, or whatever does the job for you.

Issues in producing optical systems
Once your system is designed, you have to produce it. One of the biggest issues is the lead time for obtaining glass parts, particularly lenses. Lead time may be six months, and you can't even test the design until you have real parts.

One reason for putting a radius on every lens seat is debris. Since aluminum is so widely used in the optical industry, most parts are anodized. Anodize chips off sharp edges much easier than rounded edges, especially when a lens is pushed against it. Anodize chips floating around in an optical system may prevent it from passing quality checks. Debris can come from other sources as well: Potting debris, metal shavings, clothing fibers, hair, or just plain dirt can get into a system and make optical performance unacceptable. Cleanliness is absolutely necessary, but even a strong effort to keep everything clean doesn't guarantee there will be no debris. Doing everything in a clean room won't guarantee it either. Dealing with debris takes eternal vigilance. One way of dealing with it is trapping it somewhere inside the system where it will stay out of the way and never escape. Another way of dealing with it is to make certain it doesn't end up on or near an image plane, so it will always be out of focus and hard to see.

Integration

I have never seen a new optical system go into production without an integration process. Optics being as unforgiving as they are, you just can't predict how material is going to move and change the prescription when you tighten screws or make adjustments. I have also seldom seen a lens assembly exactly match the prescription when the parts come in. Optics manufacturers tend to make glass parts toward the maximum material side of their tolerance so they can grind them down if something isn't right. That means that, once you get parts, you may have to change something in your mechanical design to make the prescription work as intended. When you actually start building a system is when you start learning the specific characteristics of that system. You may have to set specific torques for mounting screws, set adjustment specifications, write assembly procedures, test procedures, etc. You may also have to deal with purging, outgassing or sealing issues. You will determine all of the critical assembly considerations necessary to make the system work as intended. You just won't know all of this information up front. If the manager in charge of your project doesn't understand this part of the process, you're going to hear much wailing and gnashing of teeth. The test of a good design is that, once the integration process is essentially complete, the production unit is relatively easy to build and performs as intended. One critical aspect of integration is quality control. If your parts don't match the design specifications, you won't really know if your design works or not. I have been through hell trying to make a design work only to find out that the parts were wrong in the first place. Once the parts were right, it worked. Another integration issue is having lenses with similar radii which can be reversed in assembly. The optics will never work right if a lens is reversed.



There are two modeling situations that require special treatment in Solidworks: a surface against a sharp edge, and a surface against a radius.

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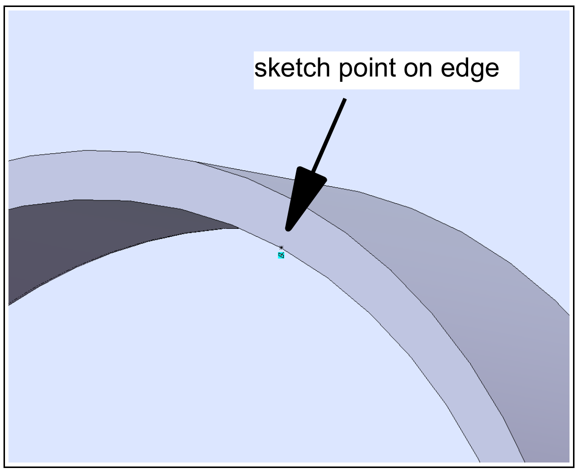
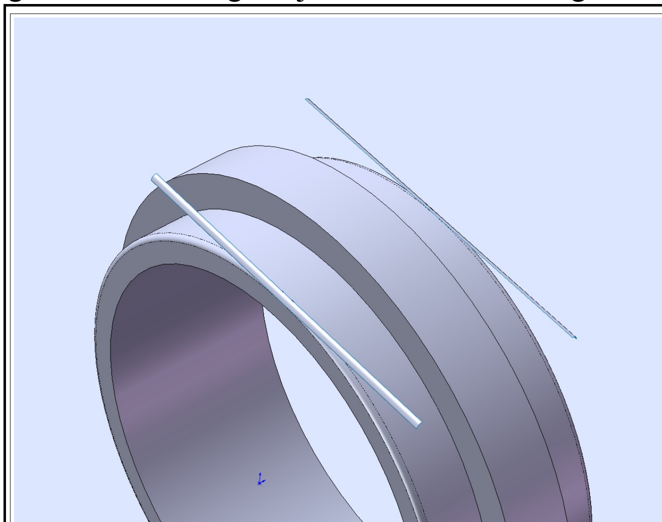
Modeling optical systems

CAD is definitely the way to go when designing an optical system. There are some caveats, however. When you model your system, assemble it the same way it will be assembled on the production floor. The production floor doesn't have reference datums, curves, points, or other imaginary CAD data available to them. They can see it on a computer screen, but they can't assemble lenses to imaginary datums. Unless you assemble lenses and other optical elements to the actual surfaces they will be assembled to in real life, you are asking for trouble. The closer your model reflects real life, the better your design will be. The other thing to watch out for is how to assemble the unit. You can design something really clever, just like the ball inside a solid cage, but if the production floor can't build it, you'll have to do it over. Just because you can design it in CAD doesn't make it producible.

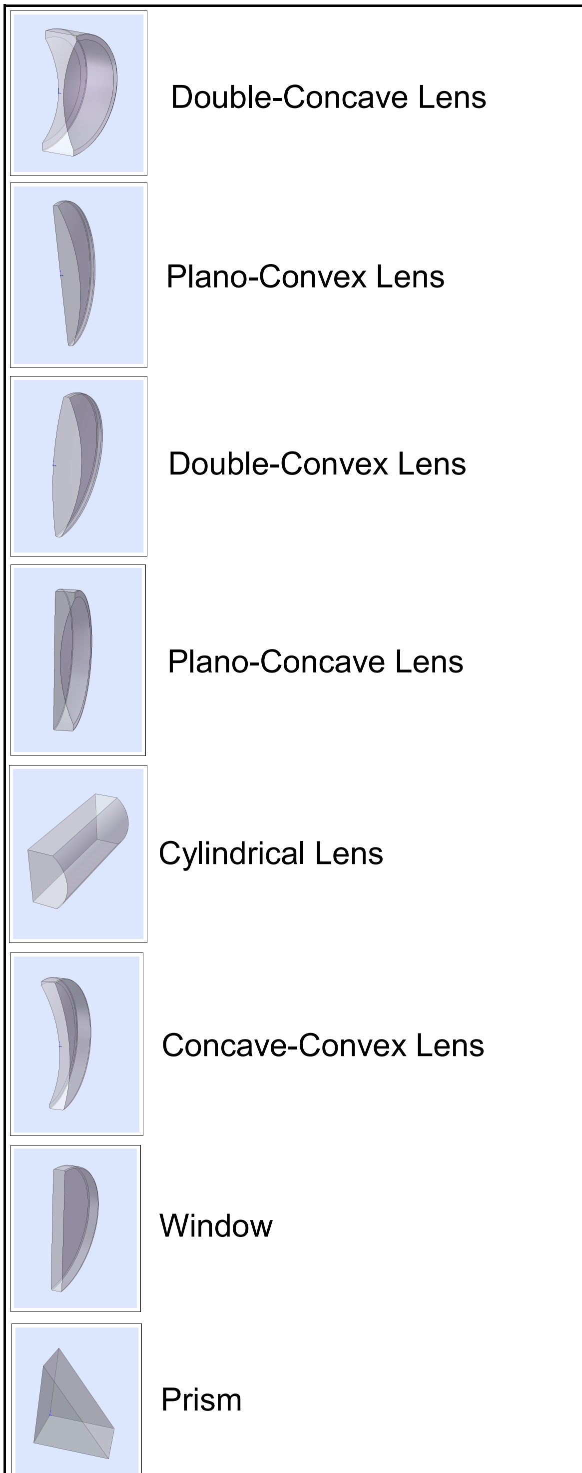


Using an edge to assemble a lens. You'll have to sketch a point on the edge, then make the lens surface coincident with the point.



Mating a lens surface to a radiused edge. You'll have to extrude a surface from an intersection curve (to keep it tied to the radius), then make the lens surface tangent to the created surface. Not ideal, but it works.

The other thing you'll have to deal with is that CAD programs don't do a good job of accommodating lens placement. You can do it, but there are tricks to learn. See the illustrations for details on using Solidworks to assemble lenses. In ProE, a simple tangent constraint will assemble a lens surface to a rounded edge, whether it's concave or convex. However, ProE also requires the use of a sketch point on an edge to assemble a lens surface to a sharp edge. I don't recommend mounting lenses against sharp edges, but you'll likely have to do it at some point. It seems that the CAD vendors are unaware of how optical elements must be assembled into a system.



Types of Optical Elements

Types of Optical Elements

Lenses, windows, mirrors, and prisms will make up the greatest part of the elements you have to mount. There are many other optical elements. Mirrors are generally a flat reflective surface, but any optical surface can be made reflective. A window is a flat piece of glass without any power. In other words, both surfaces are flat and parallel, just like a window in your house. Prisms are used as beamsplitters, reflectors, and other things. They are common in optical systems. Shown here are a few of the more common elements found in optical systems. Different elements may require unique mounting and adjustment considerations. Most of the elements shown are in cross section to clarify their shape.

Conclusion

This is a very limited treatment of packaging optical systems aimed at mechanical designers who are relatively unfamiliar with optical systems. This is just the basics. There is a lot of information I haven't touched on, but I hope this is helpful for a lot of people. If you'd like to comment on this article or have a suggestion to make it more helpful, send an e-mail to ksauter@sauterindustrialdesign.com .