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Frédéric Lamontagne, Nichola Desnoyers, Michel Doucet, Patrice Côté, Jonny Gauvin, Geneviève Anctil, Mathieu Tremblay, "Lens auto-centering," Proc. SPIE 9626, Optical Systems Design 2015: Optical Design and Engineering VI, 962619 (23 September 2015); doi: 10.1117/12.2196756

Event: SPIE Optical Systems Design, 2015, Jena, Germany

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ABSTRACT

In a typical optical system, optical elements usually need to be precisely positioned and aligned to perform the correct optical function. This positioning and alignment involves securing the optical element in a holder or mount. Proper centering of an optical element with respect to the holder is a delicate operation that generally requires tight manufacturing tolerances or active alignment, resulting in costly optical assemblies. To optimize optical performance and minimize manufacturing cost, there is a need for a lens mounting method that could relax manufacturing tolerance, reduce assembly time and provide high centering accuracy.

This paper presents a patent pending lens mounting method developed at INO that can be compared to the drop-in technique for its simplicity while providing the level of accuracy close to that achievable with techniques using a centering machine (usually < 5 µm). This innovative auto-centering method is based on the use of geometrical relationship between the lens diameter, the lens radius of curvature and the thread angle of the retaining ring. The auto-centering principle and centering test results performed on real optical assemblies are presented.

In addition to the low assembly time, high centering accuracy, and environmental robustness, the INO auto-centering method has the advantage of relaxing lens and barrel bore diameter tolerances as well as lens wedge tolerances. The use of this novel lens mounting method significantly reduces manufacturing and assembly costs for high performance optical systems. Large volume productions would especially benefit from this advancement in precision lens mounting, potentially providing a drastic cost reduction.

1. INTRODUCTION

The technique consisting of inserting a lens into a lens barrel and then securing it with a threaded ring is generally referred to as the drop-in technique. The centering precision obtained from this technique first depends on the radial gap between the lens and the barrel. Thermal effects caused by the mismatch of the respective coefficients of thermal expansion of the lens and of the barrel materials also have an impact on the centering of the lens. Manufacturing tolerances on dimensions of the assembled components such as the diameter of the lens, the diameter of the barrel cavity and the thickness difference along the edge of the lens also affect the quality of the centering. The greater the required precision on the centering of the lens, the greater the manufacturing costs of both lens and barrel.

The main advantages of the drop-in technique are that the assembly time can be very short and that the lenses are removable. Low cost drop-in, however, has the drawback of a loss in centering precision. If more precision is needed, the drop-in method may not be suitable and active alignment is required. In this centering method, the lens is first positioned inside the cavity and its decenter relative to the reference axis of the barrel is measured. The lens is then moved to reduce the centering error. Once centered, the lens is fixed in place with adhesive or other means. This method provides a very high level of centering accuracy, but requires expensive equipment while being time-consuming.

To optimize optical performance and minimize manufacturing cost, there is a need for a lens mounting method that could relax manufacturing tolerances and reduce assembly time while still providing high centering accuracy.

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Optical Systems Design 2015: Optical Design and Engineering VI, edited by Laurent Mazuray, Rolf Wartmann, Andrew P. Wood, Proc. of SPIE Vol. 9626, 962619 · © 2015
SPIE · CCC code: 0277-786X/15/$18 · doi: 10.1117/12.2196756

2. AUTO-CENTERING

2.1 Auto-centering principle

To appropriately define the lens centering error with respect to the barrel reference axis, both lens surfaces need to be considered. It has been shown that very good centering accuracy, generally less than 5 µm, can be expected for an optical surface mounted directly on the barrel seat with the drop-in method [1]. On the other hand, poor centering is typical for the second optical surface and centering errors over 100 µm are common. To improve the drop-in method performance, the lens rim is used to limit the centering error so tight tolerances on lens diameter, lens wedge and barrel bore diameter are needed. The control of the radial clearance between the lens and the barrel inside diameter (ID) yields centering errors usually between 25 and 50 µm [2], [3]. Using the novel auto-centering lens mounting method to center lenses allows taking advantage of the simplicity of the drop-in method while overcoming the drawbacks related to the poor centering precision.

The auto-centering method is based on the use of the geometrical relationship between the lens diameter, lens radius of curvature, and the thread angle of the retaining ring. The barrel's thread angle and the spatial profile of the peripheral region of the lens surface are selected to create auto-centering conditions whereby any decentering of the retaining ring and a corresponding tilt of the retaining ring have counterbalancing effects on the centering of the optical element.

The problem with using standard threaded rings is that the positioning errors of the ring lens seat affect the centering of the lens surface in contact with it in the same manner as a barrel seat. Threaded rings need clearance in the threads to allow for assembly, leaving room for it to be decentered or tilted. Figure 1 (a) shows the effect of a ring centering error on the lens centering, and Figure 1 (b) shows the effect of a ring tilt error on the lens centering.

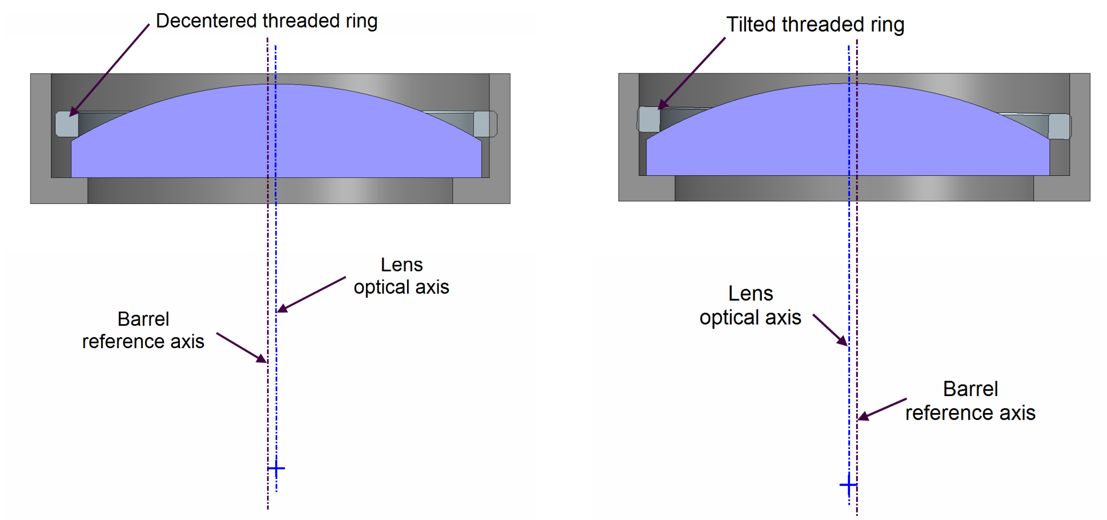

Figure 1. Impact of the ring positioning error on the lens centering (exaggerated ring displacement).

(a) Decentered threaded ring, (b) Tilted threaded ring.

A spherical lens surface constrained by a decentered threaded ring will be shifted by an equivalent amount, as express by equation (1):

$$\Delta_{ring} = \Delta_{shift} \quad (1)$$

where:

- Δ_{ring} (mm) is the lateral decentering of the retaining ring; and
- Δ_{shift} (mm) is the lateral decentering of the center of curvature of the lens surface in contact with the retaining ring;

A tilt of the retaining ring will affect the centering of the lens as expressed by equation (2):

$$\Delta_{tilt} = \sin(\theta_{ring})\sqrt{R^2 - Y^2} \qquad (2)$$

where:

- Δ_{tilt} (mm) is the lateral decentering of the center of curvature of the lens surface in contact with the retaining ring resulting from the tilted retaining ring;
- R (mm) is the radius of curvature of the lens surface in contact with the retaining ring;
- Y (mm) is the half-diameter of the retaining ring's aperture; and
- θ_{ring} (degrees) is the tilt of the retaining ring with respect to the plane perpendicular to the barrel reference axis.

When a threaded ring is tightened to secure a lens, axial forces act so that the ring is constrained by its top thread surface as shown in Figure 2.

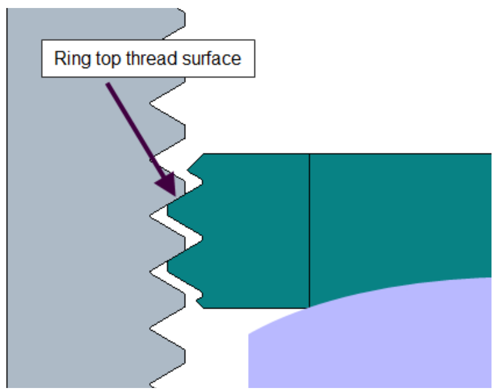

Figure 2. Threaded ring constrained by the top thread surface.

Because there is always an assembly clearance between the ring and the barrel thread, the ring is free to decenter when screwed into the barrel. The fact that the retaining ring is threaded to the barrel has means that its tilt and its lateral decentering are linked to each other in a predetermined fashion. Since the ring is constrained on the top thread surface, the ring rolls according to the thread angle when decentered as illustrated in Figure 3.

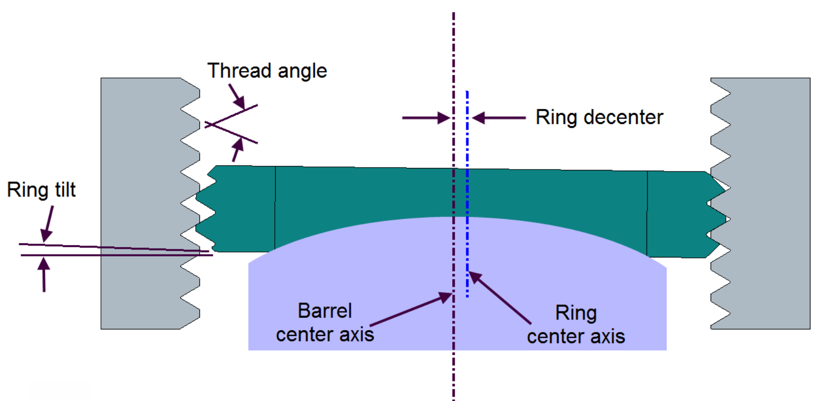

Figure 3. Relationship between the ring decenter and ring tilt.

The retaining ring is tilted clockwise if it is shifted to the right, and counterclockwise if it is shifted to the left. The relationship between the threaded ring decentering and the tilt of the retaining ring can be expressed as follows:

$$\theta_{ring} = \sin^{-1}\left[\frac{2\Delta_{ring}\, tan\left(\varphi_{threads}/_{2}\right)}{d_{ring}}\right] \tag{3}$$

where:

- θ_{ring}(degrees) is the tilt of the retaining ring as defined above;
- Δ_{ring}(mm) is the lateral decentering of the retaining ring;
- $\varphi_{threads}$(degrees) is the thread angle; and
- d_{ring} (mm) is the major diameter of the retaining ring (measured at the thread crest).

Most of the time, the ring will be decenter according the maximum clearance in the thread when screwed into the barrel. When the lens centerability criterion is met, the lens translates or rolls in order to be fully constrained by the barrel lens seat and the ring lens seat. This means that the decenter and the tilt of the ring will define the position of the lens surface in contact with the ring. The decentering Δ_{C2} of the center of curvature of the lens surface in contact with the threaded ring with respect to the barrel reference axis can be express as:

$$\Delta_{C2} = \Delta_{tilt} + \Delta_{shift} \tag{4}$$

where the sign of Δ_{tilt} and of Δ_{shift} refers to the direction of the corresponding shift.

Figure 4 shows the effect of the ring decenter and tilt on the lens centering. In the case of this bi-convex lens, the lens roll on the center of curvature of the surface in contact with the barrel seat and the surface in contact with the threaded ring is decentered as per the ring positioning error.

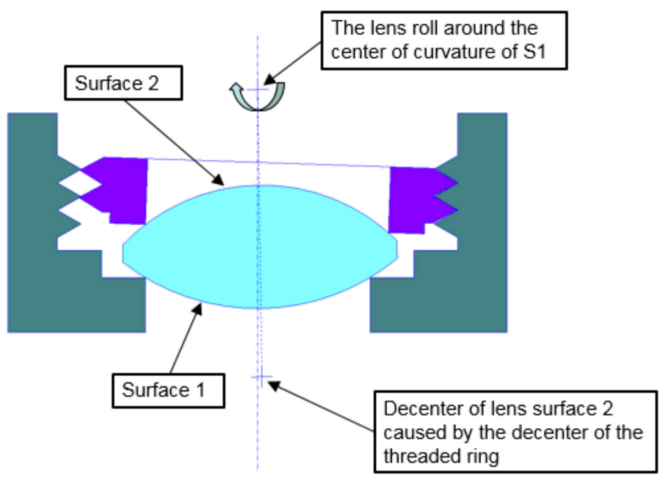

Figure 4. Effect of the ring decenter and tilt on the lens centering using classical threaded ring (exaggerated ring displacement).

Table 1 from [1] presents centering measurements for spherical convex lens surface in contact with a standard threaded ring. The centering error presented are directly related to the threaded ring decenter and tilt as described by equation 4.

Table 1. Centering measurement of a lens surface in contact with a standard threaded ring

# of measurment	Mean (µm)	Min (µm)	Max (µm)	Std deviation (µm)
36	48.9	8.2	144.2	36.1

These measurement results show that using a standard threaded ring having a thread angle of 60 degrees results in very large decentering errors of the lens surface in contact with the threaded ring.

In order for the optical element to be centered, the decentering Δ_{C2} of the center of curvature of the optical surface in contact with the ring with respect to the barrel reference axis should be made null or negligible. Knowing, as mentioned above, that the centering error Δ_{shift} of the center of curvature of the surface in contact with the ring with respect to the barrel reference axis is equivalent to the decenter Δ_{ring} of the retaining ring within the cavity, an auto-centering condition can be defined by writing equation (4) as:

$$\Delta_{tilt} = \Delta_{ring} \tag{5}$$

When the auto-centering condition is met, the decentering of the retaining ring and the corresponding tilt of the retaining ring have counterbalancing effect on the lens centering, providing a self-alignment of the lens.

It will be noted that the auto-centering condition of the present description does not rely on the centering of the retaining ring with respect to the cavity; as a matter of fact, it uses the decentering of the retaining ring in order to provide a centering of the optical element.

By combining equations (2), (3) and (5) above, the auto-centering condition can be rewritten as:

$$\frac{d_{ring}}{2\,tan\left({}^{\varphi_{threads}}/_{2}\right)} = \sqrt{R^2 - Y^2} \tag{6}$$

Equation (6) is a simplified model that does not consider the threaded ring thickness and the distance between the thread and the annular contact region between the ring and the lens. In some particular case, these parameters must be considered to achieve a high centering level. The auto-centering condition of equation (6) could be rewritten to include these parameters as:

$$\frac{d_{ring}}{2\,tan\left({}^{\varphi_{threads}}/_{2}\right)} = \sqrt{R^2 - Y^2} + h + {}^{T}/_{2} \tag{7}$$

where the parameters *h* and *T*, are represented on Figure 5:

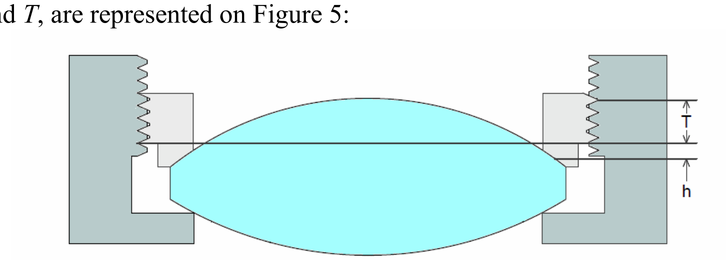

Figure 5. Additional parameters to be considered for the auto-centering condition.

The auto-centering technology takes advantage of the high precision level of the geometric tolerance that are provided by CNC lathe machine without taking any special care. Another point that makes the auto-centering lens mounting so performant is that the lens centering is not very sensitive to the manufacturing tolerances of the parameters involved. For example, the following commercial manufacturing tolerances would result in a lens decenter typically within 3 µm:

- Thread angle tolerance: ±1°;
- External diameter of the retaining ring: ±0.1 mm;
- Diameter of the aperture of the retaining ring: ±0.1 mm;
- Radius of curvature of the second surface: ±1%;

With the addition of the barrel's geometrical tolerance, the resulting centering error is typically below 5 μm, which can be considered a very performant lens mounting method in terms of centering precision.

The most performant way to meet the auto-centering condition is to adjust the thread angle as per the lens geometry. The thread angle requires to meet the auto-centering condition for a given lens geometry is given by the following equation:

$$\varphi_{threads} = 2\tan^{-1}\left(\frac{d_{ring}}{2\sqrt{R^2 - Y^2} + 2h + T}\right) \tag{8}$$

where, as explained above:

- d_{ring} is a diameter of the retaining ring along the ring threads;
- R is the value of the radius of curvature of the second surface;
- Y is the half-diameter of the retaining ring's clear aperture;
- h is the distance between (i) the first point of contact of the barrel threads with the ring threads proximate to the optical element and (ii) the point of contact of the abutment of the retaining ring with the peripheral region of the second surface; and
- T is the distance between (i) the first point of contact of the barrel threads with the ring threads proximate to the optical element and (ii) the last point of contact of the barrel threads with the ring threads farthest from the optical element diametrically opposite to the first point of contact.

Figure 6 shows the same lens barrel assembly as Figure 4 but with the difference that the thread angle has been adjusted as per equation (8) to meet the auto-centering condition. As it can be seen, the retaining ring is constrained by the ring top thread interface and the ring tilt is linked to the ring decenter and thread angle. However, even if the ring is decentered and tilted, the lens is still centered on the barrel reference axis since the auto-centering condition is met.

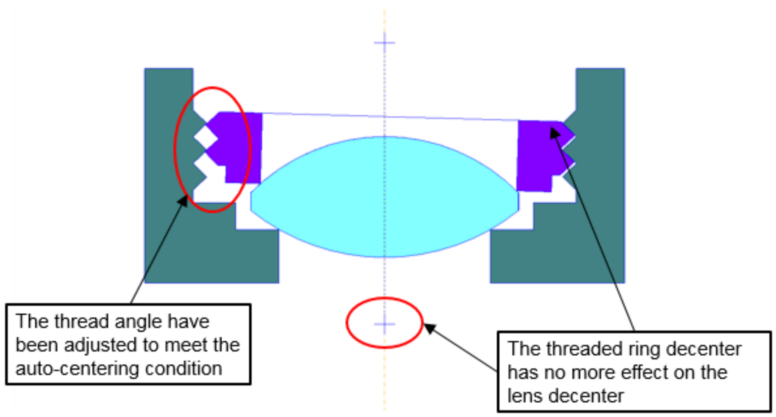

Figure 6. Auto-centered lens not affected by the ring centering (exaggerated ring displacement).

Table 2 presents centering measurements at the center of curvature of the optical surface in contact with ring using the auto-centering technique. The measurements were performed with plano-convex, meniscus, and bi-convex lenses having different diameters and radii of curvature. These data provide information about the centering accuracy for different lens geometries, the centering repeatability of assemblies using the same parts as well as manufacturing reliability for a production of a few units. A TRIOPTICS OptiCentric® MOT 100 (centration measurement instrument) having an estimated overall accuracy of ±1μm was used for the measurements.

Table 2. Centering measurement of a lens surface in contact with the threaded ring using auto-centering

# of measurment	Mean (μm)	Min (μm)	Max (μm)	Std deviation (μm)
121	3.0	0.7	6.5	1.4

These results show a very high centering accuracy of 5.8 µm at 2σ as well as a very good repeatability. This centering precision is comparable to that achievable with lens mounting using active alignment. Assembly using the auto-centering technology is performed in a few seconds without any alignment. The lenses were only dropped into the barrel and secured with a threaded retaining ring meeting the auto-centering condition. This corresponds to an overall centering precision improvement of 10 to 20 times for the auto-centering method compared to the drop-in technique relying on the retaining ring for centering.

Since the lens centering is not very sensitive to slight thread angle variation, a set of threading tools in increments of 5 degrees is usually sufficient to auto-center lens with a high precision level. Moreover, with modern CNC lathes, the infeed angle can also be used to machine different auto-centering thread angles with a single threading tool.

In other cases, a local radius can be added to the lens to perform the auto-centering as shown on Figure 7. This embodiment can be used when lens doesn't meet the centerability criterion with the optical surfaces, or to implement only standard thread angle in the lens barrel design. A chamfer can also be used instead of a radius with low effect on the centering quality since the decentering of the ring is relatively small. Also, geometrical behaviour allows using the same chamfer angle for a wide range of lens radii and diameters, limiting the numbers of different tools required to machine the chamfers.

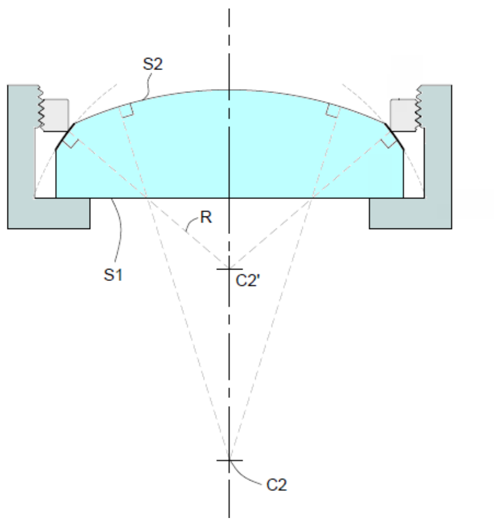

Figure 7. Auto-centering of lens using a local radius.

The local radius required to meet the auto-centering condition for a lens geometry is given by the following equation:

$$R = \sqrt{\left[\frac{d_{ring}}{2\tan\left(\varphi_{threads}/2\right)} - h - T/2\right]^2 + Y^2} \tag{9}$$

where, as explained above:

- d_{ring} is a diameter of the retaining ring along the ring threads;
- R is the value of the radius of curvature of the second surface along the peripheral region thereof;
- $\varphi_{threads}$ is a value of the thread angle of the barrel threads;
- Y is the half-diameter of the of the retaining ring aperture;
- h is the distance between (i) the first point of contact of the barrel threads with the ring threads proximate to the optical element and (ii) the point of contact of the abutment of the retaining ring with the peripheral region of the second surface; and
- T is the distance between (i) the first point of contact of the barrel threads with the ring threads proximate to the optical element and (ii) the last point of contact of the barrel threads with the ring threads farthest from the optical element diametrically opposite to the first point of contact.

The centering error of the local radius or chamfer relative to the lens optical axis affects the centering error of the lens once mounted in the barrel. This makes the use of the optical surface for ring interface more accurate for the auto-centering.

2.2 Stress on lens

With the standard drop-in method, the lens rolls or translates to marry the threaded ring seat position. But since the standard thread angles are not matched with the radius of curvature, the lens decenters until the barrel bore stops the displacement of the lens. In that case, the forces act asymmetrically and the ring applies force locally on the lens's optical surface. In the case of the auto-centering method, the force is distributed uniformly over the annular contact between the lens and the ring, reducing the stress applied on the optical element.

2.3 Centerability criterion

The INO auto-centering technology is a cost effective way to assemble lenses with very low centering error. This technology is applicable to a wide range of lens shapes as long as the criterion of centrability is respected.

With the auto-centering, the lens is mounted on a barrel seat and secured by a retaining ring. When the clamping angle is large enough to overcome the friction force between the lens and the mechanical parts, the lens rolls or translates when the threaded ring is screwed until the lens is fully constrained by the barrel seat and the ring seat. This condition has to be met to perform the auto-centering.

The limit of centrability depends on the coefficient of friction between the lens and the mechanical parts as well as dynamic effects involved in the assembly of the threaded ring. Simple relations with the static coefficient of friction cannot be done. For that reason, it is more appropriate to define the criterion of centrability in terms of a minimum clamping angle that must be met instead of a coefficient of friction (as generally done by lens manufactures for bell clamping method). The clamping angle α is formed by the tangents to the surfaces S1 and S2 on both sides of the lens at the clamping radius Y_{c1} and Y_{c2} as shown on Figure 8.

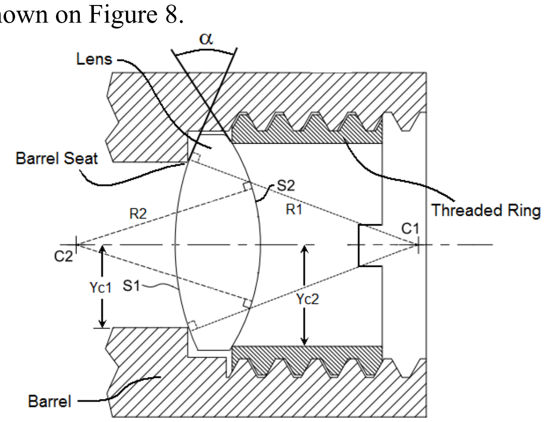

Figure 8. Criterion of centrability parameters

The clamping angle can be defined for different lens geometries as per Figure 9 adapted from [4].

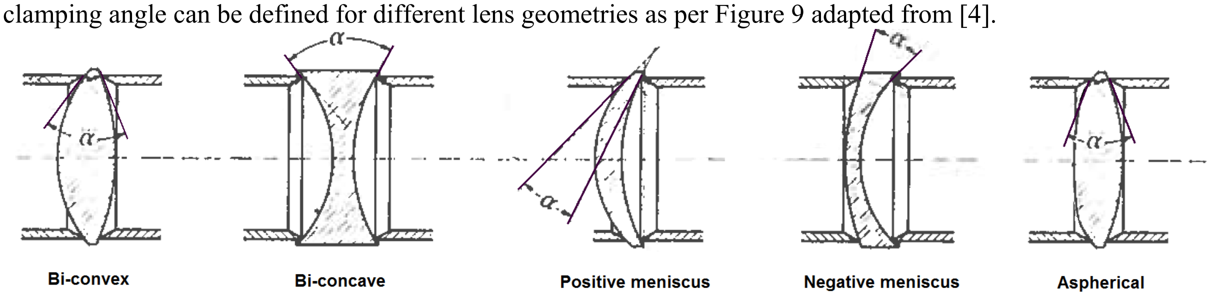

Figure 9. Clamping angle α for different lens types [4].

The lens clamping angle can be expressed as:

$$\alpha = \left| sin^{-1}\left(\frac{Y_{c1}}{R_1}\right) + sin^{-1}\left(\frac{Y_{c2}}{R_2}\right) \right| \quad (10)$$

where:

- α is the lens clamping angle define by the surface tangents at the Y_{c1} and Y_{c2} radius;
- Y_{c1} is the half-diameter of contact of the first surface S1 of the optical element with the seat;
- Y_{c2} is the half-diameter of contact of the second surface S2 of the optical element with the retaining ring;
- R_1 is the radius of curvature of the first surface of the optical element; and
- R_2 is the radius of curvature of the second surface of the optical element.

It is to be noted that in equation (10) the radius of curvature has a positive value for convex surfaces and a negative value for concave surfaces.

The clamping angle threshold that allows the use of the auto-centering technology has been determined experimentally using high friction optical coatings and high friction anodizings, corresponding to combination of worst cases when used with various lens clamping angle α.

The tests were conducted with lens samples having several optical coatings and with aluminum parts having various surface treatments. More than twelve different lens samples with distinct clamping angles from 6.5 degrees up to 16 degrees have been selected and tested with three optical coatings and three anodic processes.

Table 3 presents the optical coatings and aluminum surface treatments used for the tests.

Table 3. Selected surface treatments and anodizing processes for test campaign

Surface Treatment Applied on Lenses	
Surface Treatment #1	AR visible MgF2 E-Beam evaporation
Surface Treatment #2	IAD visible BBAR SiO2 (Ion Assisted Deposition)
Surface Treatment #3	uncoated
Anodic Processes Applied on Threaded Ring and Barrel	
Process #1	Optical Black from Pioneer Metal
Process #2	Low reflection anodic coating from Bodycote
Process #3	Black anodize, MIL-A-8625F Type II, Class 2, Nom. Th. 15 µm

Surface treatment #1 and #2 are commercial optical coatings reputed for high friction coefficient. Anodic process #1 and #2 are anodic metal coating used in optical assemblies to minimize the stray light reflection. Anodic process #3 is used for more general applications where the protection of the aluminum is the first goal rather than the optical performance. The test campaign includes more than 200 measurements. Results of the tests show that a minimum clamping angle of 14.0 degrees is required to meet the criterion of centrability allowing the use of the INO auto-centering technology.

Therefore, the minimum clamping angle to use the INO auto-centering technology can be expressed as:

$$\alpha = \left| sin^{-1}\left(\frac{Y_{c1}}{R_1}\right) + sin^{-1}\left(\frac{Y_{c2}}{R_2}\right) \right| \geq 14.0° \quad (11)$$

Some lenses without optical coating have been auto-centered successfully with clamping angle value as low as 7.8 degrees. This means that the clamping angle limit of 14.0 degrees could be reduced if coatings having lower coefficients of friction are used. In such cases, a test is required to identify the appropriate minimum clamping angle for these specific coatings. Also, more advanced assembly methods (using vibrations for instance) may reduce the clamping angle threshold value in specific cases.

Table 4 shows a summary of the test results. The minimum clamping angles required to perform the auto-centering technology for each optical coating and aluminum surface treatment combination are presented. Also, the static and dynamic coefficient of friction measured for each combination are provided as reference. These coefficients have been measured using the tilted plane method.

Table 4. Minimum clamping angle measurement results

Optical coating	Aluminum surface treatment	Minimum clamping angle (degree)	Average Measured Static coefficient of friction*	Average Measured Dynamic coefficient of friction**
MgF2	MIL-A-8625F	14.0	0.375	0.145
MgF2	Pioneer Metal	14.0	0.294	0.144
MgF2	Bodycote	11.6	0.344	0.124
SiO2	MIL-A-8625F	11.6	0.205	0.121
SiO2	Pioneer Metal	14.0	0.218	0.133
SiO2	Bodycote	13.0	0.212	0.126
Uncoated	MIL-A-8625F	7.8	0.165	0.112
Uncoated	Pioneer Metal	9.3	0.146	0.102
Uncoated	Bodycote	9.3	0.169	0.104

***: All Static friction measurements fit within an interval of -0.043/+0.047**

****: All dynamic friction measurements fit within an interval of -0.006/+0.012**

2.4 Auto-centered lens barrel

Figure 10 presents an example of a lens barrel having 5 auto-centered lenses. Each lens has been disassembled and reassembled 5 times to show the repeatability level. The lens diameter varies from 18 mm to 50 mm. The lens barrel length is 55 mm, the larger outside diameter is 58 mm and the wall thickness is 0.75 mm. The barrel has been machined in a 6061-T6 aluminum rod. The radial clearance between the lens and the barrel is around 1 mm but smaller gaps can also be used to minimize the barrel volume.

Lens surface #	# of Trial	Min (μm)	Max (μm)	Ave (μm)
1	5	4.7	5.6	5.1
2	5	3.8	5.7	4.8
3	5	0.4	3.4	1.8
4	5	1.9	6.2	4.2
5	5	1.7	2.9	2.1
6	5	3.3	4.9	4.1
7	5	1.3	4.7	3.3
8	5	0.8	3.3	2.3

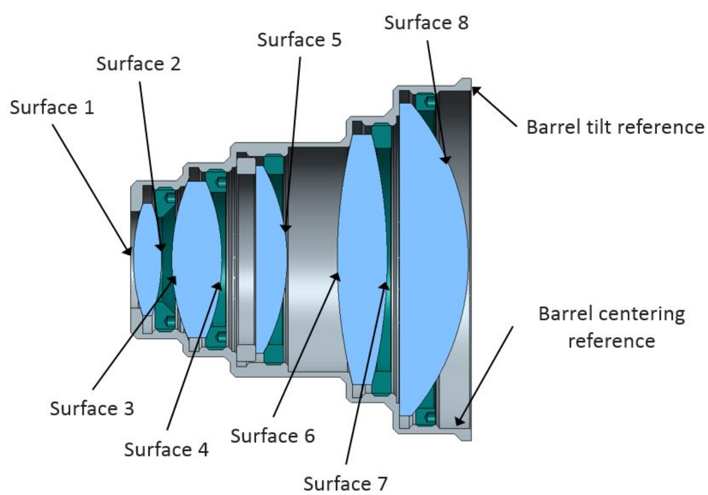

Figure 10. Centering results for a lens barrel using auto-centering technology.

Results show very high centering accuracy for lens surface in contact with the barrel seat as well as for surfaces in contact with the threaded ring using the auto-centering technology.

2.5 Applications

The auto-centering lens mounting method can be used with spherical, aspherical, and cylindrical lenses, with any lens geometry, provided the centrability criterion is met. Most lens shapes are supported, including:

- Plano-convex
- Bi-convex
- Plano-concave
- Bi-concave
- Positive meniscus
- Negative meniscus

The auto-centering technology is very flexible to lens diameter. In fact, the technology can be implemented for any lens diameter where a threaded ring can be used to constraint the lens axially. Typically, lenses from 10 mm to 150 mm can be auto-centered easily.

Also, the technology can accommodate almost any lens radius of curvature as long as the centerability criterion is met. For very small or very large radius of curvature, asymmetrical thread profiles as shown on Figure 11 are used to solve manufacturing issues.

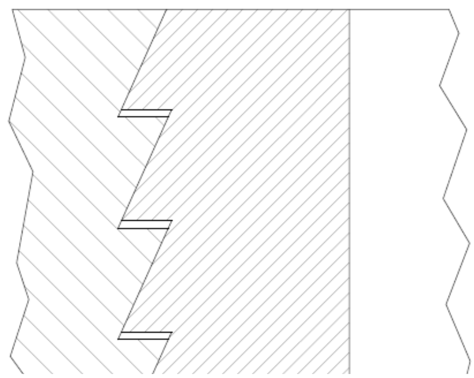

Figure 11. Asymmetrical thread profile used for very small radius of curvature

Negative thread angles as illustrated on Figure 12 are used to auto-center concave lens surfaces.

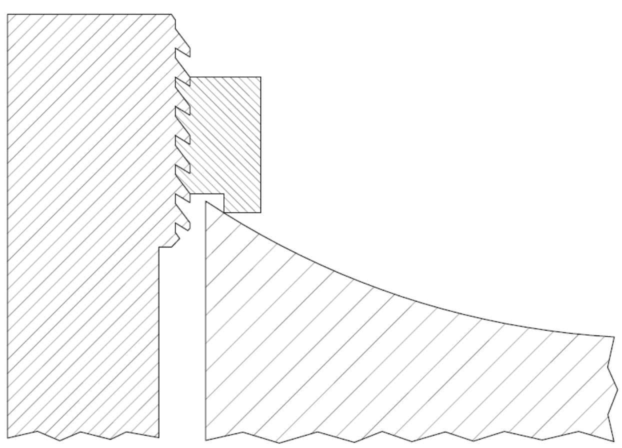

Figure 12. Negative thread profile for concave lens surface

To control the tilt of planar lens surfaces, Buttress thread profile as illustrated on Figure 13 are used.

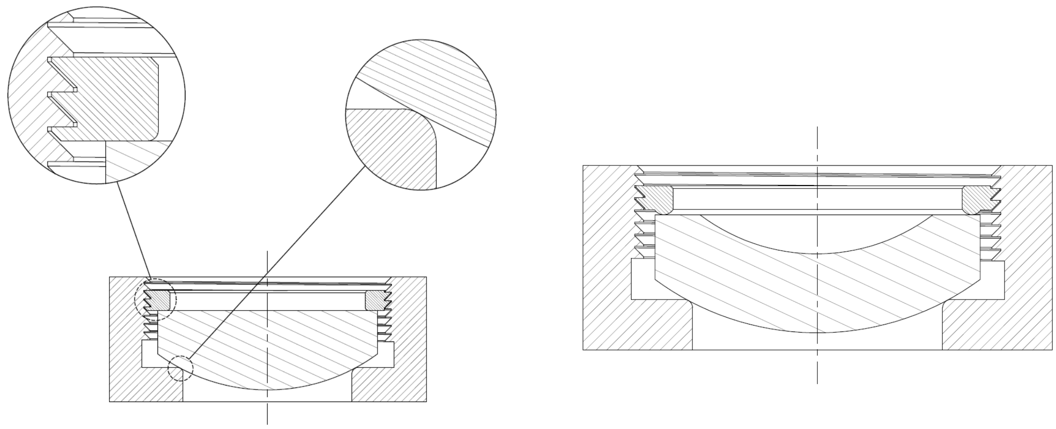

Figure 13. Buttress thread profile for concave and plane lens surface

Different thread pitches can also be used. Thread pitches of 0.5 mm, 0.8 mm and 1.6 mm have been tested successfully at INO.

Also, different types of lens contacts such as sharp edge, tangent or toroidal can be used on the barrel seat as well as on the ring interface with the lens.

Finally, optical sub-assemblies can be auto-centered in the same manner as lenses by adding a spherical surface at the threaded ring interface that meet the auto-centering condition as shown on Figure 14.

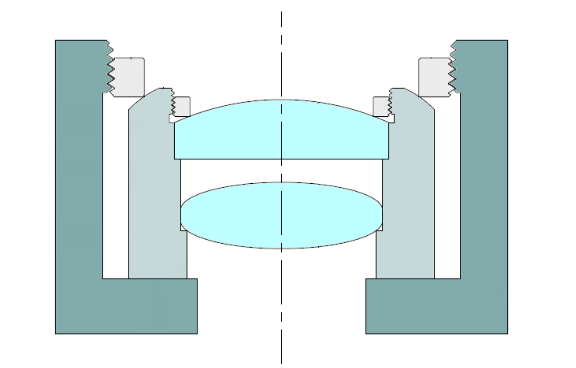

Figure 14. Auto-centering of an optical sub-assembly in a barrel

2.6 Robustness

Environmental tests have been performed on a lens barrel assembly having a N-BK7 plano-convex lens of 40 mm diameter. A first centering measurement has been performed prior the environmental test. Then, the centering was verified after each test. The following tests were performed :

- Storage temperature range :
  - MIL-STD-810G, Method 501.5, +71C, 7 cycles, 3hrs stabilization
  - MIL-STD-810G, Method 502.5, -40C, 1 cycles for 24hrs
- Vibration exposure :
  - MIL-STD-810G, Method 514.6, General minimum integrity exposure, One hour per axis, rms = 7.7 gs
- Vibration & temperature
  - Vibration 7.7 Grms, 20 – 2000 Hz, 1 hour, 1 axis, +71C
  - Vibration 7.7 Grms, 20 – 2000 Hz, 1 hour, 1 axis, -40C

- Drop test :
  - 1 meter height
  - 1 drop on each axis (total of 3 drops)
  - Drop test performed on a 2” thick hardwood backed by concrete

The Table 5 presents the centering error measured after each tests.

Table 5. Auto-centering environmental testing

Environmental test	Centering (μm)
Initial lenses auto-centering prior environmental tests	3.17
After cold temperature: -40C, 1 cycle for 24hrs	3.32
After hot temperature: +71C, 7 cycles	2.44
After vibration: 7.7Grms, 3 axis, 1 hour per axis	3.85
After vibration at high temperature: 7.7Grms 1 hour, 1 axis, +71C	4.63
After vibration at low temperature: 7.7Grms 1 hour, 1 axis, -40C	2.94
After drop tests: 1 meter height, 3 axis	3.15

There is no significant observable decentering caused by the environmental tests. Variations of each measurement are on the order of magnitude of the measurement error. These results shows that the auto-centering lens mounting method is very robust to thermal variations, vibration, and shock.

2.7 Benefit

With the auto-centering lens mounting method, it takes only a few seconds to achieve centering accuracy comparable to active alignment. Since the method is using the lens optical surfaces as mounting interface, the lens wedge, the lens diameter and the barrel bore diameter tolerances can be relaxed, reducing the manufacturing cost of the optical components. The method also allows easy lens unmounting for rework or for maintenance. Moreover, a common technique to reduce sensitivity to alignment error in order to use the low cost drop-in method is to add lenses to the optical assembly during the design process. With INO’s high precision alignment method, fewer lenses may be considered to meet the optical requirement and further reduce the manufacturing cost.

2.8 Auto-centering Portfolio

The INO auto-centering technology is covered by four patents pending. In addition to the low cost and the high precision lens centering provided by the auto-centering lens mounting, the technology has been extended to other application where centering precision is a challenge. As shown on Figure 15, the auto-centering technology can be applied to lens spacers, providing better control of the air gap precision between lenses. Multiple barrels can also be assembled into each other with a centering error less than 5 μm. INO has also developed machining methods allowing the flip a lens barrel on the CNC lathe while keeping concentricity error lower than 5 μm between both sides of the barrel. Finally, translatable sleeves can also be auto-centered, providing an axial adjustment of an optical group without compromising the centering accuracy. The solution can also be applied for auto-centered zoom and focus mechanisms.

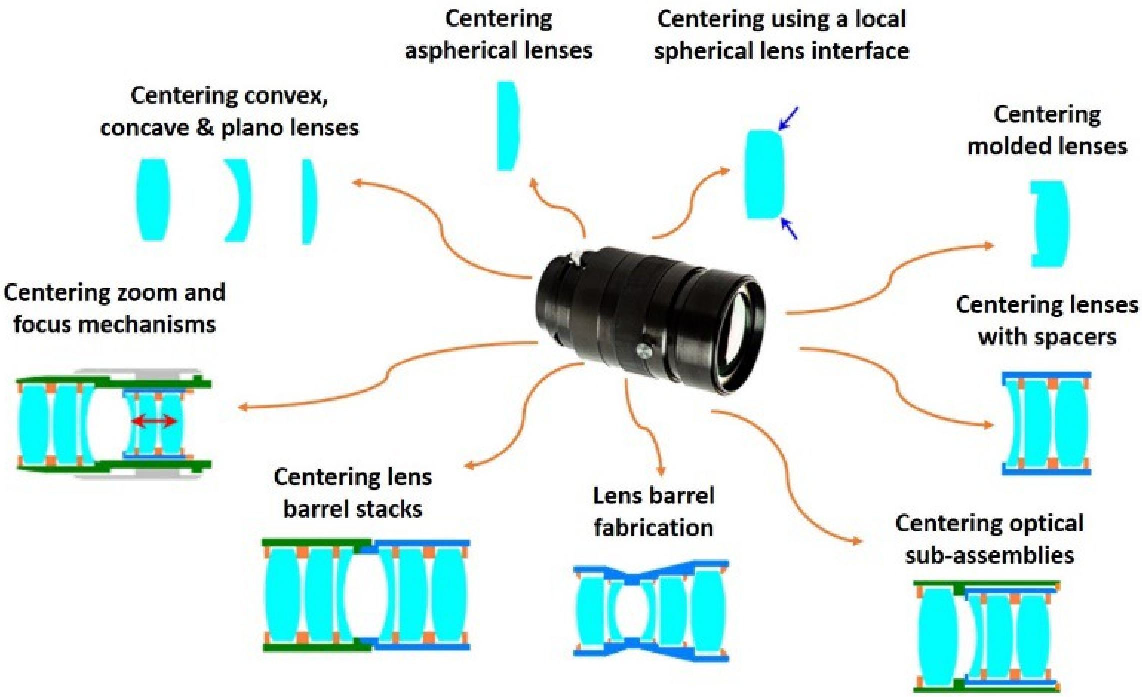

Figure 15. Auto-centering technology portfolio

3. CONCLUSION

A new lens mounting method that combines the advantages of the drop-in method and the centering precision of active alignment has been presented. This innovative method uses the thread of the retaining ring as a mechanical reference surface to center the lens. The barrel thread angle and the spatial profile of the peripheral region of the lens surface are selected to create auto-centering conditions whereby any decentering of the retaining ring and a corresponding tilt of the retaining ring have counterbalancing effects on the centering of the optical element. Centering measurements performed with the auto-centering method have shown a very high centering accuracy of 5.8 μm at 2σ as well as a very good repeatability. This new lens mounting method has the advantage of providing very accurate centering while relaxing the manufacturing tolerances on lens wedge, lens diameter and barrel bore diameter as required for the drop-in method. The auto-centering method results in a high precision centering method at a low manufacturing cost.

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