High Precision Lens Mounting

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1. Review of common lens mounting methods
2. Optical surface lens mounting
3. Auto-centering lens mounting
4. Auto-centering of optomechanical parts
Lens Mounting Method Overview

- An increase of centering precision results in an increase of cost and complexity
  - Tight manufacturing tolerance
  - Active alignment

<table>
<thead>
<tr>
<th>Lens mounting method</th>
<th>Centering precision</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drop-in</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Lathe assembly</td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Active alignment</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Subcell lens assembly</td>
<td>High</td>
<td>High</td>
</tr>
</tbody>
</table>

- Auto-centering lens mounting
  - Centering accuracy of $\sim\pm 5 \, \mu m$
  - Cost similar to loose tolerance drop-in
Optical Surface Mounting

- The auto-centering uses lens surface-contact mounting method
  - Lens mounted directly on optical surfaces
  - Centering not influenced by lens edging error
  - Centering not influenced by radial clearance between lens and barrel
The clamping angle at the lens and mechanical seat need to be large enough to overcome the friction force.

The minimum clamping angle that allows the use of the auto-centering technology has been determined experimentally using typical high friction optical coatings and high friction anodizings (static coefficient of friction as high as 0.375).

Test results show that a minimum clamping angle of **14 degrees** is needed to use the auto-centering technology.

Optical Surface Mounting Centerability Criterion
The lens centering accuracy of the lens surface in contact with the barrel seat is influenced by the manufacturing errors of the barrel seat concentricity and tilt error.
**Classical Optical Surface Mounting: Barrel seat**

- Centering measurement of a lens surface mounted on the **barrel lens seat**
  - Typically less than 5 µm

### Decenter measurements of the lens surface mounted on barrel seat

<table>
<thead>
<tr>
<th>Lens diameter (mm)</th>
<th>Radius of curvature (mm)</th>
<th>Lens surface decenter (µm)</th>
<th>Lens surface tilt (arcmin)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>64.6</td>
<td>0.4</td>
<td>0.02</td>
</tr>
<tr>
<td>50</td>
<td>64.6</td>
<td>1.9</td>
<td>0.10</td>
</tr>
<tr>
<td>50</td>
<td>64.6</td>
<td>1.7</td>
<td>0.09</td>
</tr>
<tr>
<td>50</td>
<td>64.6</td>
<td>2.1</td>
<td>0.11</td>
</tr>
<tr>
<td>50</td>
<td>64.6</td>
<td>1.9</td>
<td>0.10</td>
</tr>
<tr>
<td>50</td>
<td>90.4</td>
<td>3.4</td>
<td>0.13</td>
</tr>
<tr>
<td>50</td>
<td>90.4</td>
<td>2.1</td>
<td>0.08</td>
</tr>
<tr>
<td>50</td>
<td>90.4</td>
<td>2.4</td>
<td>0.09</td>
</tr>
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</table>
Optical Surface Mounting: Threaded Ring

• The ring is constrained by the ring top thread surface
• Ring can be decentered and tilted because of the assembly clearance
• The ring tilt is linked to the ring decenter by the thread angle

\[
\theta_{\text{ring}} = \sin^{-1}\left[\frac{2\Delta_{\text{ring}} \tan\left(\frac{\varphi_{\text{threads}}}{2}\right)}{d_{\text{ring}}}\right]
\]
• Centering measurement of a lens surface in **contact with a threaded ring**
  o Poor centering provided by threaded ring
  o Radial clearance need to be control to reduce the centering error

**Decenter measurements of the lens surface mounted on threaded ring**

<table>
<thead>
<tr>
<th># of measurement</th>
<th>Decenter Mean (µm)</th>
<th>Decenter Min (µm)</th>
<th>Decenter Max (µm)</th>
<th>Std deviation (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>48.9</td>
<td>8.2</td>
<td>144.2</td>
<td>36.1</td>
</tr>
</tbody>
</table>

Measurement accuracy of ±1 µm
Auto-Centering Lens Mounting

- Lens simply dropped in barrel and secured with a special threaded ring
- Ring and barrel **thread angles are adjusted** to meet the auto-centering condition
Auto-Centering Lens Mounting

- Centering measurement of a lens surface in contact with a special threaded ring using auto-centering technology
  - High centering accuracy (**5.8 µm at 2σ**) (Classical Threaded ring)
  - Loose diameter and lens wedge tolerances
  - No alignment (INO Auto-centering)
  - Do not rely on radial clearance

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<th>Decenter Max (µm)</th>
<th>Std deviation (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>121</td>
<td>3.0</td>
<td>0.7</td>
<td>6.5</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Measurement accuracy of ±1 µm
The auto-centering condition occurs when the ring decenter and the corresponding ring tilt have counterbalancing effect on the lens centering error:

\[ \Delta_{Ring\ Decenter} = \Delta_{Ring\ Tilt} \]
Auto-centering Principle

• The auto-centering condition can be rewritten considering the geometrical parameters as:

\[
\frac{d_{\text{ring}}}{2 \tan\left(\frac{\varphi_{\text{threads}}}{2}\right)} = \sqrt{R^2 - Y^2}
\]

• In order to meet the auto-centering condition for a given lens, the thread angle of the retaining ring is adjusted:

\[
\varphi_{\text{threads}} = 2 \tan^{-1}\left(\frac{d_{\text{ring}}}{2\sqrt{R^2 - Y^2}}\right)
\]
AUTO-CENTERING TECHNOLOGY

https://www.youtube.com/watch?v=S7oOa_79fIs
Lens Barrel Auto-Centering

- Lens assemblies are much more complex than a simple convex lens to be centered
- The principle has been extended to other applications where centering precision is a challenge:
  - Optical sub-assembly
  - Translatable Optical Group
  - Barrel stack
Auto-Centering Portfolio

• INO auto-centering is covered by 2 patents and 3 pending patents
• The auto-centering technology can be applied to different optical and optomechanical components:
Auto-Centering of Optical Sub-Assembly

- Centering of optical sub-assembly in main barrel are traditionally controlled using pilot diameters
- 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
- Centering error typically less than 5 µm
Translatable Optical Group

- The use of thread as mechanical positioning reference allows to combine the centering of an optical sub-assembly with an axial adjustment within the main barrel
  - A buttress thread having a surface perpendicular to the barrel axis is used for the axial displacement
  - The centering of the translatable group can be provided by the use of a threaded ring and a spherical interface
Auto-centering of Lens Tubes

• The use of thread as mechanical positioning reference can be used to mount lens barrels to each other
  o The two barrels interface to each other with a spherical interface
  o The remaining rotation degree of freedom is constrained by the buttress thread that have surface contact perpendicular to the barrel reference axis
Auto-centering of Lens Tubes

• Tests have been performed to verify the centering accuracy that can be expected with this barrel stack mounting method
• Barrels of 60 mm long having diameter of 50 mm have been assembled to each other
• The method provides a centering error typically less than 5 µm

<table>
<thead>
<tr>
<th>Barrel’s stack combination #</th>
<th># of Trial</th>
<th>Decenter Min (µm)</th>
<th>Decenter Max (µm)</th>
<th>Decenter Ave (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>2.2</td>
<td>3.3</td>
<td>2.7</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>3.2</td>
<td>4.3</td>
<td>3.8</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>1.8</td>
<td>3.7</td>
<td>2.8</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>2</td>
<td>3.4</td>
<td>2.7</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>1.9</td>
<td>3.2</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Measurement accuracy: ±1 µm
Lens Barrel Fabrication

A method can be used for machining both sides of a lens tube with a typical centering error of ±5 µm.

Examples of double-side machined barrel measurements

<table>
<thead>
<tr>
<th>Barrel Sample #1</th>
<th>Decenter (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentricity #1</td>
<td>0.2</td>
</tr>
<tr>
<td>Concentricity #2</td>
<td>2.59</td>
</tr>
<tr>
<td>Concentricity #3</td>
<td>0.14</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Barrel Sample #2</th>
<th>Decenter (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentricity #1</td>
<td>1.17</td>
</tr>
<tr>
<td>Concentricity #2</td>
<td>1.44</td>
</tr>
<tr>
<td>Concentricity #3</td>
<td>2.72</td>
</tr>
</tbody>
</table>

Measurement accuracy: ±1 µm
Lens Barrel Optomechanical Design

- 6 lenses barrel
  - Convex
  - Concave
  - Planar
- The lens assembly is auto-centered on a lens mount
- Axial adjustment between the barrel 1 and barrel 2
- Optical sub-assembly auto-centered in barrel 1
Lens Barrel Optomechanical Design

• The whole lens barrel assembly in mounted using a threaded interface on an optical system.
• Lens 5 is a bi-convex lens auto-centered with a ring having a thread angle of 30 degrees.
• Lens 6 is a negative meniscus that have a thread angle of 20 degrees.
• The barrel 1 is mounted on barrel 2 using a threaded interface allowing to perform an axial adjustment between the two barrels.
Lens Barrel Optomechanical Design

- Lens 3 is a bi-concave lens auto-centered with a ring having an negative thread angle.
- Lens 4 is a plano-convex lens where the planar surface tilt is controlled by a buttress thread.
- Standard threads of 60 degrees are used to auto-center the optical sub-assembly according to the barrel 1 reference axis.
Lens Barrel Optomechanical Design

- Lens 1 is a positive meniscus auto-centered with a thread angle of 75 degrees
- Lens 2 is another bi-convex lens which is auto-centered using a thread angle of 50 degrees
Common lens mounting method
  - An increase in centering precision results in an increase of cost

INO Auto-centering technology
  - ~±5 μm high-accuracy centering without active alignment
  - < 25 sec assembly time per lens secured in place
  - Relaxation of tolerances of lens wedge and diameter
  - Relaxation of tolerances on barrel bore diameter

This novel optomechanical mounting approach open new possibilities to realize a variety of different high precision lens assemblies at lower cost
### Auto-centered Lens Barrel Example

- Centering results for a 5 lenses barrel using auto-centering technology

#### Decenter measurements for a 5 lenses barrel

<table>
<thead>
<tr>
<th>Lens surface #</th>
<th># of Trial</th>
<th>Decenter Min (µm)</th>
<th>Decenter Max (µm)</th>
<th>Decenter Ave (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>4.7</td>
<td>5.6</td>
<td>5.1</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>3.8</td>
<td>5.7</td>
<td>4.8</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>0.4</td>
<td>3.4</td>
<td>1.8</td>
</tr>
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<td>5</td>
<td>1.9</td>
<td>6.2</td>
<td>4.2</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>1.7</td>
<td>2.9</td>
<td>2.1</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>3.3</td>
<td>4.9</td>
<td>4.1</td>
</tr>
<tr>
<td>7</td>
<td>5</td>
<td>1.3</td>
<td>4.7</td>
<td>3.3</td>
</tr>
<tr>
<td>8</td>
<td>5</td>
<td>0.8</td>
<td>3.3</td>
<td>2.3</td>
</tr>
</tbody>
</table>

Measurement accuracy of ±1 µm
Environmental tests have been performed on a lens barrel
- N-BK7 plano-convex lens of diameter 40 mm
- There is no significant decentering observed caused by the environmental tests

<table>
<thead>
<tr>
<th>Environmental Test</th>
<th>Decenter (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial lens decenter</td>
<td>3.17</td>
</tr>
<tr>
<td>After cold temperature: -40°C, 1 cycle for 24hrs</td>
<td>3.32</td>
</tr>
<tr>
<td>After hot temperature: +71°C, 7 cycles</td>
<td>2.44</td>
</tr>
<tr>
<td>After vibration: 7.7Grms, 3 axis, 1 hour per axis</td>
<td>3.85</td>
</tr>
<tr>
<td>After vibration at high temperature: 7.7 Grms, 1 hour, 1 axis, +71°C</td>
<td>4.63</td>
</tr>
<tr>
<td>After vibration at low temperature: 7.7Grms, 1 hour, 1 axis, -40°C</td>
<td>2.94</td>
</tr>
<tr>
<td>After drop tests: 1 meter height, 3 axis</td>
<td>3.15</td>
</tr>
</tbody>
</table>

Measurement accuracy of ±1 µm
The auto-centering can be performed using different threaded ring thickness

- The auto-centering can be performed using different thread pitch
  - 0.5mm, 0.8 and 1.6mm thread pitch have been tested
- The auto-centering has been tested on lens diameters ranging from 5 mm to 100 mm
- The auto-centering can be used for any radius of curvature as long as the centrability criterion is met (clamping angle of 14 degrees)
- The auto-centering can be achieved using a ring with flexure
Technology Implementation

• Manufacturing tolerances
  o The auto-centering Technology takes advantage of the intrinsically high level of precision offered by lathes for single setup lens tube manufacturing
  o The accuracy is not sensitive to dimensional manufacturing errors
  o The auto-centering accuracy depends only on the geometrical manufacturing errors such as the concentricity and the perpendicularity of the lens seat and thread with respect to the barrel reference axis
The auto-centering equation is used to calculate the optimal thread angle according to lens geometrical parameters

$$\frac{d_{ring}}{2 \tan(\frac{\phi_{threads}}{2})} = \sqrt{R^2 - Y^2} + h + T/2$$

In most cases, thread angle increments of 5 degrees are sufficient to perform the auto-centering technology, limiting the number of threading tools required.
Custom thread angle profiles

- INO has developed custom thread angle profiles inspired on ASME and ISO standard
- A spreadsheet is used to calculate the manufacturing parameters according to the thread pitch and the thread angle
  - Thread depth
  - Major diameter
  - Pitch diameter
  - Minor diameter
  - Thread tolerances

Technology Implementation

30 deg custom thread profile

90 deg custom thread profile
Technology Implementation

- Thread tooling
  - Simple; Affordable

- Different thread angles can be machined using a single tool using flank infeed or thread curve profile on CNC turning machine

Radial infeed

Flank infeed
Technology Implementation

• Thread inspection
  o Go-No Go manufacturers have been contacted
  o Custom angle thread Go-No Go can be use for inspection