7.4 Tilt Adjustment Mechanisms

**General Description**

Tilt adjustments of optical components such as mirrors, lenses, prisms, and diffraction gratings are frequently required to optimize the image quality in optical systems. A tilt mechanism can be designed to provide an adjustment about one axis or two mutually orthogonal axes. As mentioned earlier, tilt and linear adjustment mechanisms are quite similar in design and basically use the same kind of components. The design factors for selecting a suitable type of component for tilt mechanisms are the same as for the linear mechanisms. If an adjustment mechanism is designed with three mutually orthogonal adjustment points, it can be used to perform linear as well as tilt adjustments. When the three actuators are moved equally, a linear movement results. However, if only one of the actuators is moved, a tilt adjustment about an axis defined by the two others is achieved. The parts, which can be used as the basic building blocks for tilt adjustment mechanisms, are discussed briefly in this section. Also, some examples of tilt mechanisms are presented to demonstrate the basic design principles.

**Interfaces for Tilt Mechanisms**

The tilting component can be attached to a fixed structure through rotary bearings (journal, ball, roller, air), flexures (Bendix, flat blade), or a traditional kinematic interface. The trade-offs for these types of interfaces have already been discussed under linear mechanisms. A number of commercial single and two-axis tilt stages are available. These tilt stages employ a semikinematic interface between the fixed base and the moving tilt platform. The construction of a typical two-axis tilt stage is shown in Figure 7.31. The three-point interface between the tilt and fixed plates consists of hemispherical balls, which locate into a cone, a v-groove, and on a flat surface of the fixed plate. Two of the balls are rounded tips of the micrometers or fine pitch screws, and are positioned on mutually orthogonal axes with respect to the fixed ball. The interface between the two plates is preloaded by two extension springs located midway between the fixed and moving contact points.

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*Figure 7.30 A fine-focus mechanism using differential threads for camera objective lenses.*
Various configurations of flexures can also be used to attach the tilting part to the fixed structure. For small angles of rotation, a flexure strip shown in Figure 7.32 can be analyzed by the same equations used for beams that have end loads. If the axial load at the end is zero, the tilt angle $\theta$ is given by:

$$\theta = \frac{12ML}{Ebt^3}$$

where $M =$ the applied bending moment
$L =$ the length of the flexure
$E =$ the elastic modulus of flexure material
b = the width of the flexure

A two-strip flexure pivot, shown in Figure 7.33, can be used for small tilt angles. This type of flexure is commercially available in the form of a pivot bearing. For a given tilt angle $\theta$, the required bending moment $M$ for a compressive load $P$ can be calculated from the following equations:

$$ M = \frac{EI\lambda}{2} \left[ \frac{L\lambda}{2} + \cot \frac{L\lambda}{2} \right] \theta $$  \hspace{1cm} (13)

If $P$ is a tensile load, then the moment $M$ is given by:

$$ M = \frac{EI\lambda}{2} \left[ \coth \frac{L\lambda}{2} - \frac{L\lambda}{2} \right] \theta $$  \hspace{1cm} (14)

where

$I$ = the moment of inertia of the single strip
$E$ = the elastic modulus of strip material

The parameter $\lambda$ in these equations is defined by the following expression:

$$ \lambda = \frac{P}{\sqrt{EI}} $$

A right circular flexure, shown in Figure 7.34, can be used in applications requiring a well-defined center of rotation and high stiffness. For this special configuration of the flexure, the center of the cutting radius $R$ lies on the edge of the flexure. The bending stiffness of this flexure can be estimated by:

$$ \theta = \frac{9\pi MR^{0.5}}{2Ebt^{2.5}} $$  \hspace{1cm} (15)
where $M =$ the applied bending moment  
$R =$ the cutting radius  
$E =$ the elastic modulus  
$b =$ the width of the flexure  
$t =$ the flexure thickness

**Actuators for Tilt Mechanisms**

The actuators suitable for linear mechanism can also be used in tilt mechanisms. The screws and micrometer adjustments are used in manual mechanisms, and are extensively employed in commercial tilt stages and mirror mounts. Once again, the motorized actuators are large in size and expensive, and are used when real-time and frequent adjustments are required.

**Coupling Methods for Tilt Mechanisms**

As in linear mechanisms, the rounded tip of the actuator can bear against a flat or a conical surface in tilt mechanisms. The flat surface has high contact stresses, while a conical seat provides an increased contact area to minimize the contact stresses in those tilt mechanisms, which are adjusted frequently or require a higher load capacity.

**Preloading Methods for Tilt Mechanisms**

The preloading methods employed in linear mechanisms can also be used in tilt mechanisms. These include springs and washers as discussed in Section 7.3. The extension or compression springs can be centered between two adjacent actuators to achieve a uniform preloading. For smaller tilts and higher preloads, stacked Belleville or curved washers can be used in place of springs. The advantages and disadvantages of these preloading methods have already been discussed under linear adjustment mechanisms.

**Locking Methods for Tilt Mechanisms**

The locking methods for tilt mechanisms are similar to those employed in the linear adjustment mechanisms. These include set screws, jack screws, locknuts, and epoxy. The set screws and locknuts are used for temporary locking in coarse adjustment tilt mechanisms. The epoxy locking is economical and simple in design but is used in those mechanisms which are adjusted at initial assembly and alignment only, and do not require to be disassembled. As in linear mechanisms, a
closed-loop control system can be used for motorized actuators to retain the desired tilt adjustment in real-time position control applications.

Examples of Tilt Adjustment Mechanisms

The conceptual designs of a number of tilt adjustment mechanisms are described in this section. As mentioned earlier, these examples are meant as guidelines only and a designer will most likely have to size the components of the mechanism according to the desired performance requirements. Moreover, a number of components from different mechanisms presented here can be combined to optimize the design for the application on hand. In some cases, the design of a single adjustment point is presented. As mentioned earlier, three mutually orthogonal adjustment points are needed to achieve a tilt adjustment along two mutually orthogonal axes. These three adjustment points must be spaced as far apart as possible on the optical mount to improve the angular resolution of tilt adjustment.

A very simple single-axis tilt mechanism for a flat mirror is depicted in Figure 7.35 for nonprecision applications. The lower edge of the mirror is rounded and sits in a v-groove in the mount. A single round tip adjustment screw threaded through the mount acts at the center of top edge of the mirror causing the mirror to pivot about its lower edge. A sheet metal spring clip is employed to preload the mirror against the adjustment screw and the v-groove. A locknut is used to retain the adjusted position and to secure the spring clip to the mount. The lateral shift of the mirror can be minimized by making the length of the v-groove approximately the same as the width of the mirror. Moreover, the in-plane movement of a flat mirror can be tolerated in most applications. The negative features of this low-cost simple adjustment mechanism are the special machining features required at the top and bottom edges of the mirror, and a low accuracy of the adjustment. Since the mirror is retained by frictional force only, it is not suitable for shock and vibration environments, where it may shift and lose its alignment.

![Figure 7.35 A low-precision single-axis tilt mechanism for a mirror.](image)

The design of a simple two-axis tilt mechanism, similar to a commercial tilt stage described earlier, has been reported by Walsh. The piano wire acts as a universal pivot between the moving and fixed plates (Figure 7.36). The two plates must be spring loaded against each other by providing two extension springs located between the adjustment screws and the piano wire. Fine threaded screws with round tips can be used to improve the resolution of tilt adjustment. One screw tip sits in a v-groove, while the other screw tip contacts the flat surface of the moving plate. It may be
more economical to buy a commercial tilt stage as compared to fabricating this tilt adjustment mechanism.

The design of a high precision single-axis tilt adjustment mechanism has been reported by Nemirovsky. The interface between the tilt platform and the fixed base is through steel balls (Figure 7.37[A]). The top ball on the right side is spring loaded to eliminate backlash. A fine-threaded screw pushes on the lower ball, which is wedged under the middle ball, resulting in a tilt motion about the left-side ball. This mechanism has tilt resolution of the order of a fraction of an arc-second. A number of variations of this design are possible. The balls can be replaced by precision centerless ground shafting with tapered ends. The adjustment screw can have a round tip, thereby eliminating the need for a separate lower ball (Figure 7.37[B]). The screw can also be replaced by a rod with a tapered end to produce a jacking action (Figure 7.37[C]). This mechanism is useful in applications requiring single-axis tilt adjustments of a high accuracy over a limited angular travel.

James and Sternberg have described the design of a simple two-axis tilt mechanism as shown in Figure 7.38. Three mutually orthogonal fine screws with ball tips provide a kinematic interface between the mirror cell and fixed structure. The mirror cell is spring loaded against the screws using a compression spring at the center. After making the tilt adjustment, the adjustment screws are locked by means of locknuts. Care must be taken to ensure that the adjustment is not lost due to excessive locking force. This is a good low cost mechanism for low accuracy applications.

FIGURE 7.36 A simple two-axis tilt mechanism with a universal pivot.

FIGURE 7.37 A high-precision mechanism for small tilt angles using: (A) two spring-loaded steel balls; (B) a round tip screw and a spring-loaded ball; (C) a tapered rod and a spring-loaded ball.
The adjustment mechanism shown in Figure 7.39 can be designed to achieve very fine tilt adjustments due to a lever arrangement with a high mechanical advantage. It employs two flat blade flexures. The lower flexure is compliant in bending, while the vertical flexure is very stiff in tension. Coarse adjustment is provided by a regular nut threaded to the top end of vertical flexure. A locknut is provided to retain this coarse adjustment. Fine adjustment is made by a spring-loaded screw, which bends the horizontal flexure. By making $R/r$ ratio equal to 10, 5 μm of vertical travel is obtained for every 50 μm of travel of the fine adjustment screw. The cost of this mechanism is comparatively higher due to the number of parts in it.

Another tilt mechanism using flat blade flexures is illustrated in Figure 7.40. The two flexures are riveted or welded together to fix their lower edges. A spring-loaded adjustment screw is threaded into the fixed structure through a clearance hole in the flexures. The top edge of smaller flexure is rigidly attached to the fixed part using two screws and a pin to prevent any slippage. The top edge of the longer flexure is fixed to the tilting part in the same fashion. When the screw is threaded in to bend the flexures, a very small relative motion is produced between the free edges of flexures, thereby causing the moving part to tilt. A very fine adjustment can be achieved for a relatively large travel of the adjusting screw by properly sizing the flexures. This mechanism is rather expensive to fabricate, and is suitable for applications requiring high stiffness and accuracy over a limited travel range.

Figure 7.41 shows the design of a tilt adjustment mechanism reported by Ahmad for a high resonance adjustable mirror mount. The mirror is suspended in its cell by three tangent bars with a pair of circular cross-flexures at each end. One end of each bar is secured to the invar buttons bonded directly to the mirror, while the other end is attached to the fixed structure. These tangent bars are very stiff in tension and compression, while they are relatively quite compliant in bending normal to the plane of the mirror. A small differential micrometer pushes on each invar button through a compliant flexure to eliminate lateral loads and misalignments. Each invar button is spring loaded against the tip of the micrometers. A high resolution tilt adjustment can be made by moving one differential micrometer at a time. This expensive tilt adjustment mechanism is recommended for high resonance precision applications.
FIGURE 7.39 A tilt mechanism with coarse and fine adjustments using single blade flexures.

FIGURE 7.40 A tilt mechanism with a fine adjustment capability over small angles.
7.5 Rotary Adjustment Mechanisms

General Description

Rotary adjustment mechanisms are not as commonly used in optical systems as the linear and tilt adjustment mechanisms. For flat optics such as fold mirrors, windows, filters, and prisms, an in-plane rotation does not produce any change in alignment, and hence the system performance is unaffected. Similarly, for spherical optics such as lenses and mirrors, any rotation about the optical axis does not produce or correct any optical aberration. For off-axis and aspheric optics, normally linear and tilt adjustment mechanisms are employed to align the optical systems. In general, rotary mechanisms are used in scanning applications such as bar-code scanners in supermarkets and scanning telescopes and cameras for surveillance and remote monitoring, or for optical beam steering.

A number of choices are available to a designer for selecting the components of a rotary mechanism depending on the performance requirements such as frequency, range, and resolution of angular travel, shock, load capacity, cost, and size of the mechanism. A number of components that are used in linear mechanisms can also be used in rotary mechanisms, either in the same configuration or in their rotary version. These design choices along with some design guidelines are discussed in this section, followed by examples of some simple rotary mechanisms.

Interfaces for Rotary Mechanisms

The choice of a suitable interface between the rotating part and the fixed structure depends on such design criteria as the range and frequency of adjustment, shock, load capacity, cost, and size requirements. As in the case of linear mechanisms, rotary versions of the bearings discussed in Section 7.3 are commonly used to interface the rotating part to the fixed part. Spherical and journal bearings are only used for light duty cycles because of the friction and wear problems. These bearings are compact in size and are inexpensive as compared to rotary ball, roller, and air bearings, which are used in those applications where heavy loads are adjusted frequently or require continuous rotation.
A high speed rotary mechanism using a ball bearing has been described by Weinreb.\textsuperscript{26} Figure 7.42 shows the radiometer spindle assembly for TIROS II meteorological satellite. The chopper mirror is mounted to a shaft supported by a ball bearing and is driven by a low power motor at a speed of 2750 rpm. Since this mechanism operates in space, lubrication of bearings is critical to minimize the wear for a long life and to maintain the alignment of the mirror. The ball bearing in this application is constantly lubricated in space by employing a lubricant reservoir of oil-impregnated sintered nylon.

Rotary air bearings offer high stiffness and load capacity, accuracy, and cleanliness. Motorized air bearings are frictionless and use a thin film of clean dry air at a pressure of 80 to 100 psig. One such motorized air bearing by Dover Instrument Corporation is shown in Figure 7.43.\textsuperscript{27} The bearing assembly consists of a load-carrying section, a spindle housing, and a motor housing. The air-bearing part consists of a shaft and two thrust plates. The shaft, thrust plates, and the inside surfaces of the housing are machined flat and cylindrical to tolerances of 10 micro-in. The air is fed through jeweled orifice restrictors into the clearance between shaft and the housing. The clearance between rotating elements and spindle housing is of the order of 5 to 10 \( \mu \text{m} \). When compressed air passes through this clearance, a positive film pressure is created around the rotating shaft. This film of high pressure air acts like a very stiff spring to prevent any mechanical contact between the rotating parts and the housing, thereby creating a zero-friction condition. This compact bearing assembly comes with a built-in motor and encoder. These types of bearings are ideal for high speed applications requiring vibration-free rotation. The main disadvantage is that these bearings needed a supply of pressure-regulated clean air, which adds to the overall cost due to the equipment needed for air supply.

For small angular adjustments, a flexural pivot (Bendix type) offers the advantages of friction and backlash-free angular adjustment. These commercially available pivots are small in size and have low hysteresis. The application of these pivots in a mirror mount has been described by Rundle\textsuperscript{28} in detail.

**Actuators for Rotary Mechanisms**

The actuators used in rotary mechanisms are very similar to those used in linear mechanisms discussed in Section 7.3. Screws are used in low cost applications for small angular adjustments. Micrometers and differential micrometers are used when a more precise adjustment with a readout...
is required. Commercially available rotary stages use both types of micrometers extensively. A typical commercial rotary stage is illustrated in Figure 7.44. It provides full $360^\circ$ rotation about a vertical axis, and typically runs on a ball bearing. The angular resolution depends on the type of actuator used. A thumb screw is used for locking the adjusted position. Once again, the motorized actuators such as DC and stepper motors are used in applications requiring large and frequent angular travels or for real-time adjustments.

**Coupling Methods for Rotary Mechanisms**

Some coupling methods for linear mechanisms discussed in Section 7.3 can also be used in rotary mechanisms. For small angular travels, the round tip of an actuator can bear against a flat surface, cone, or a spherical socket. The advantages and disadvantages of these arrangements have already been discussed earlier. These interfaces can only be used for very small angular adjustments, since

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FIGURE 7.43 (A) The cross section of a high speed motorized rotary air bearing. (Courtesy of Dover Instrument Corporation, Westboro, MA.)
the tip of the actuator slides relative to the rotating part and cannot maintain a good contact with the rotating part for larger angles.

For large, frequent, or constant angular motion, an actuator can be coupled to the rotating part through a flexible type of coupling. The choice of coupling type depends on the radial load, torque

FIGURE 7.43 (B) Picture of a high speed motorized rotary air bearing. (Courtesy of Dover Instrument Corporation, Westboro, MA.)

FIGURE 7.44 A typical single-axis commercial rotary stage. (Courtesy of Newport Corporation, Irvive, CA.)
Flexible-type couplings can tolerate relatively large misalignment between the axes of rotation of the actuator and the moving part. The performance of the systems using a flexible coupling depends on the inertia, backlash, friction, and linearity of the coupling used. It should be noted that couplings designed for motion control applications may not be suitable for power transmission and vice versa. The couplings illustrated in Figure 7.45 are suitable for rotary mechanisms and exhibit low inertia, zero backlash, and near-constant velocity. The principle disadvantages of couplings are their relatively large size, weight, and cost.

Sometimes linear actuators are used in rotary mechanisms because of their lower cost and compact size. In such cases the linear motion of the actuator is converted to a rotary movement through a worm and gear or a rack and pinion arrangement. In these mechanisms, the part to be rotated is attached to the rotating gear while the linear actuator moves the rack. These mechanisms are expensive because of their mechanical complexity and exhibit backlash, if not designed properly.

**Preloading Methods for Rotary Mechanisms**

The selection of a proper preloading method to obtain a backlash-free rotary adjustment is based on the same design factors that are discussed in Section 7.3 for the linear mechanisms. The tension or compression springs are extensively used for preloading purposes because of their low cost, and also because these can be used over a fairly large angular range. The Belleville washers are used for high preloads over small adjustment ranges. For larger angular rotations, a torsion spring can be used for preloading the rotating part. One end of the spring is attached to the rotating part, while the other end is attached to the fixed structure.
**Locking Methods for Rotary Mechanisms**

The design factors affecting the choice of suitable locking methods for rotary mechanisms are similar to those in the linear mechanisms as already discussed in Section 7.3. These factors include travel range and frequency, size and cost, and disassembly requirements.

The locking can be accomplished by set screws, clamps, epoxy, and locknuts. The relative advantages and disadvantages of all these locking methods have already been discussed. Epoxy locking is inexpensive, but it is more or less permanent, because the parts cannot be disassembled without a risk of damage. The other locking methods are nonpermanent and less expensive, but may introduce high stresses due to clamping force in the components being locked.

**Examples of Rotary Adjustment Mechanisms**

Tuttle\(^\text{10}\) has suggested the designs of a number of simple rotary mechanisms for angular positioning as shown in Figures 7.46 to 7.49. For small angular adjustments, the lever and shaft arrangements shown in Figures 7.46 and 7.47 are simple and cost effective. Two opposing tangent screws are used in the mechanism shown in Figure 7.46. The round tip of the screw pushes on a lever that rotates on a precision journal or ball bearing through small angles, while the opposing screw is moved out. The screws are locked in place by locknuts to hold the adjusted position. This low precision, low cost mechanism is suitable for infrequent adjustments over small angular travels.

In the mechanism shown in Figure 7.47, the resolution of adjustment can be improved by using the fine pitch threads. In this mechanism, the threaded sleeve is spring-loaded against the stationary

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*FIGURE 7.46* A simple rotary mechanism using tangent screws for small angular travels.

*FIGURE 7.47* A rotary mechanism using a fine-pitch screw for a limited travel range.
half to eliminate any backlash. When the sleeve is rotated in either direction, a change in the length of the screw produces a small angular rotation about the center of rotation. The angular resolution of this mechanism can be further improved by incorporating a differential screw. This mechanism is also suitable for applications requiring infrequent adjustments over small angles.
A worm and gear-type mechanism illustrated in Figure 7.48 provides an angular adjustment over full 360°. A worm mounted on an axially loaded shaft engages with a gear rotating on a bearing. The worm shaft with a reduced diameter is used intentionally to reduce its bending stiffness. The shaft is loaded axially with Belleville spring washers against a ball, which acts as a thrust bearing at the end of the shaft. Due to this spring load, the shaft operates in a slightly deflected shape to ensure a positive contact between the worm and gear. A knob attached to the shaft is rotated to produce the angular rotation of the gear. The angular resolution of this mechanism depends on the gear ratio selected. This mechanism is more expensive due to its mechanical complexity, but it does provide angular adjustments over full 360°, as stated earlier.

A very simple mechanism for one-time coarse angular adjustment is depicted in Figure 7.49. It consists of two concentric rings with a number of same-diameter holes on bolt circles of equal diameters. One of the rings has one hole less than the other ring. The locking is accomplished by lining up one set of holes in both rings, and then inserting a screw or pin through both rings. The number of holes \( n \) determines the angular adjustment step between any two adjacent locking positions, and is given by \( 360/n(n - 1) \).

Figure 7.50 illustrates a rotary mechanism using a spherical bearing. The mirror cell has an integral hemispherical ball which sits in a spherical seat in the fixed structure. This arrangement not only allows the mirror to be rotated about its optical axis, but also allows it to be tilted. This mechanism is spring loaded at the center to hold the adjustment. This low precision mechanism has a high friction and is therefore suitable for infrequent angular adjustment.

7.6 Design Guidelines for Adjustment Mechanisms

An adjustable optical mount is inherently more complex, expensive, and less stable than a comparable fixed type of mount. Therefore, a careful trade-off design study must be conducted to weigh the benefits of an adjustable optical mount against the potential stability and cost drawbacks. A good summary of how and when adjustment mechanisms must be incorporated in optical systems has been presented by Ahmad\(^{14}\) and Vukobratovich\(^{30}\).

The decision to use adjustable optical mounts is dictated by the sensitivity analysis performed by an optical designer. This analysis defines the assembly tolerances for an optical system to achieve its image resolution and quality requirements. For systems with high image resolution requirements, usually the alignment tolerances of the optical elements exceed the practical fabrication tolerances for the optical elements and the associated mechanical hardware. This problem is further compounded by the stack-up of machining tolerances and inspection uncertainties when an optical system has a large number of mirrors and lenses. In such applications, it is economical and time saving to manufacture the optical and mechanical parts to rather loose tolerances and provide
adjustments for a few sensitive optical elements. These elements are then adjusted to compensate for the errors and uncertainties in the positions of other optical elements. Therefore, a rigorous optical sensitivity analysis must be performed to identify the optical elements that have the strongest effect on image quality of the system.

The required accuracy of adjustment is usually dictated by the type of an optical element and performance requirements of the optical system. Table 7.8 by Vukobratovich\textsuperscript{30} gives general guidelines for the type of adjustment required and its sensitivity for different types of optical elements. Once the types of adjustments required for an optical element have been determined, the next step is to design an adjustable mount to provide the desired adjustment range and resolution. The glass optical elements are normally assembled in a metal frame, and an adjustment mechanism is provided between the frame and the fixed mounting structure. This way, a direct contact between the actuator and the glass element is avoided, and the element is protected from high contact stresses at the tip of the actuator. Providing an adjustment range, which is longer than that determined by the optical sensitivity analysis, can be very risky. Such mounts can be assembled far away from their required nominal position, and a lot of time may be wasted during alignment to obtain any image at all. In such cases, it is better to design the mount so that it can be shimmed at assembly, in case the range of adjustment is found to be inadequate. After an optical system has been aligned, the adjustable mounts must be positively locked to prevent any misalignment due to accidental tweaking or any drifts as a result of shock and vibrations. The adjustments, which are used only at initial assembly, can be designed to have lockable mounts with removable actuators. This approach not only saves on the cost of actuators, but also eliminates the risk of accidental misadjustment later on.

### Table 7.8 Types of Adjustments Required and Their Sensitivity

<table>
<thead>
<tr>
<th>Type of Optical Element</th>
<th>Adjustment Sensitivity</th>
<th>Type of Adjustment Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat window</td>
<td>Very low</td>
<td>Tilt</td>
</tr>
<tr>
<td>Field lens</td>
<td>Low</td>
<td>Tilt and decenter</td>
</tr>
<tr>
<td>Flat mirror</td>
<td>Medium</td>
<td>Tilt</td>
</tr>
<tr>
<td>Prism</td>
<td>Medium</td>
<td>Tilt</td>
</tr>
<tr>
<td>Objective lens</td>
<td>High</td>
<td>Tilt, decenter, and despace</td>
</tr>
<tr>
<td>Relay lens</td>
<td>High</td>
<td>Tilt, decenter, and despace</td>
</tr>
<tr>
<td>Curved mirror</td>
<td>Very high</td>
<td>Tilt and despace</td>
</tr>
</tbody>
</table>

The adjustable mounts should be designed to tilt or rotate about the principal points to avoid cross-talk between axial and tilt adjustments. The cross-coupling of adjustments can be very frustrating because several iterations of tilt and axial adjustments may be needed to achieve the alignment. The adjustable mirror mounts must be designed to tilt a mirror about its vertex to avoid an unwanted image shift. The adjustment points in a tilt mechanism should be positioned in a mutually orthogonal pattern relative to the axis of the optical element. Such mounts are easy to adjust and produce predictable movements.

The adjustment mechanisms must be designed to have a large mechanical advantage such that a large axial movement or rotation of the actuator will incrementally move the optical element. This design feature can also save valuable alignment time because there is a less likelihood of accidentally overshooting the optimum position. If feasible, the mechanisms must be designed to have a coarse as well as a fine adjustment. The coarse alignment can be quickly achieved by using the coarse adjustment, while the fine part of the adjustment is only used to optimize the quality of the image.

A number of translation, rotary and tilt stages, mirror, lens, and gimbal mounts are available commercially. These mounts are economical, precise, and quite rugged, and are very suitable for prototypes and laboratory setups. Their main disadvantage is their bulky size and weight, which makes their use impractical in the systems with several optical elements that are packaged together.
tightly. If weight and size are not a problem in an application, it is far more economical and time saving to use commercial mounts rather than designing and fabricating the custom adjustable mounts. Locking can be added to these commercial mounts, if needed.

While the adjustment mechanisms offer several advantages, the disadvantages of the adjustable mounts must not be overlooked, and provisions must be made in their design to minimize their negative effects on the optical system. First of all, the number of adjustable optical elements in a system must be kept to an absolute minimum. This not only saves on the fabrication cost, but also maximizes the long-term stability of the system. The adjustable mounts are less rigid and less stable than the fixed type of mounts and therefore experience a drift with time. The adjustments often induce nonlinear and unpredictable effects in optical systems. The adjustable mounts are mechanically weak and are more susceptible to drifts due to shock loads, vibrations, and temperature variations.

7.7 Summary

The adjustment mechanisms play an important role in the integration and alignment of sophisticated optical systems which have tight positioning tolerances. By incorporating these mechanisms in the optomechanical design, it becomes feasible and economical to produce and assemble such optical systems to very high alignment accuracies, which in turn greatly enhances the image quality of these systems. The design guidelines for three basic types of adjustment mechanisms have been presented. The design choices for various components that make up the linear, rotary, and tilt adjustment mechanisms have been listed. The advantages and disadvantages of these choices have been presented to help a designer in choosing the most suitable parts of the adjustment mechanism for a particular application.

The designs of a number of sample linear, tilt, and rotary mechanisms have also been described in this chapter. These designs cover low cost and low resolution applications and the precision mechanisms with a fine resolution for high performance applications. Some mechanisms presented here may be employed without any modification to satisfy a particular need, while in other cases the components with desirable features can be selected from different mechanisms to design a custom mechanism with optimum features for a particular application. The size and shape of the components in a mechanism are dictated by the space constraints. Therefore, in most applications it may be necessary to select or design the components to satisfy the space requirements.

The design guidelines for how and when adjustment mechanisms must be incorporated into optical systems have also been discussed. By following these simple design guidelines, the performance and image quality of a system can often be optimized at a minimum cost. The intelligent use of adjustment mechanisms can result in lower fabrication costs and a considerable reduction in the time and effort involved in alignment of precision optical systems.

References