Design of a drive for the 4-eye mechanism
Spartan IR Camera for the SOAR Telescope

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1 Definitions

The locations of the four detector locations, named A1, A2, B1, and B2, are shown in Figure 2.

Between the wide-field and high-res configurations, the focal surface tilts along an axis, which is vertical in the middle panel of Figure 2 and 17 mm behind the focal surface. The pyramidal mirror moves the rotation axis for each detector and complicates visualization.

The axle, a Henein compound flexure pivot[1] (Figure 1, is made of a single piece of aluminum, and it has built-in stops. One stop is on a curved part of the axle, and the other is on a straight part. Since the rotation is $+4.0^\circ$ (right-handed) for the wide-field configuration, the circular stops of the axles touch for the A detectors, and the straight stops touch for the B detectors. In the high-res configuration, the stops are reversed, and the rotation is -4.7°. Since the rotation angles are different in magnitude for the two configurations, the axles are different for the A and B detectors. See Figure 2 for the identifying notch.

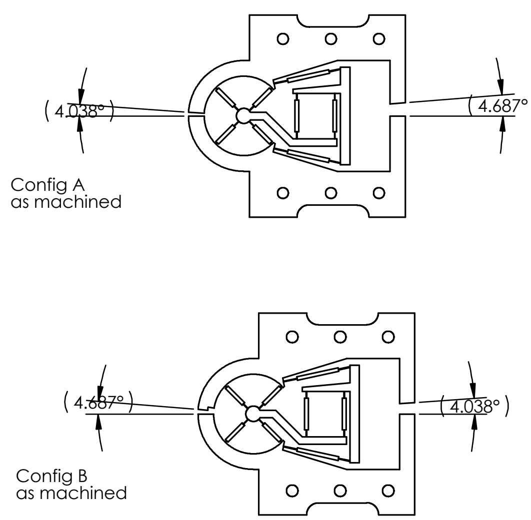

Figure 1: The flexible bearings, as they were machined.

[1] Henein, S., 2000, Conception des structures articulées à guidages flexibles de haute précision, Ph. D. Thesis, École Polytechnique Fédéral de Lausanne.

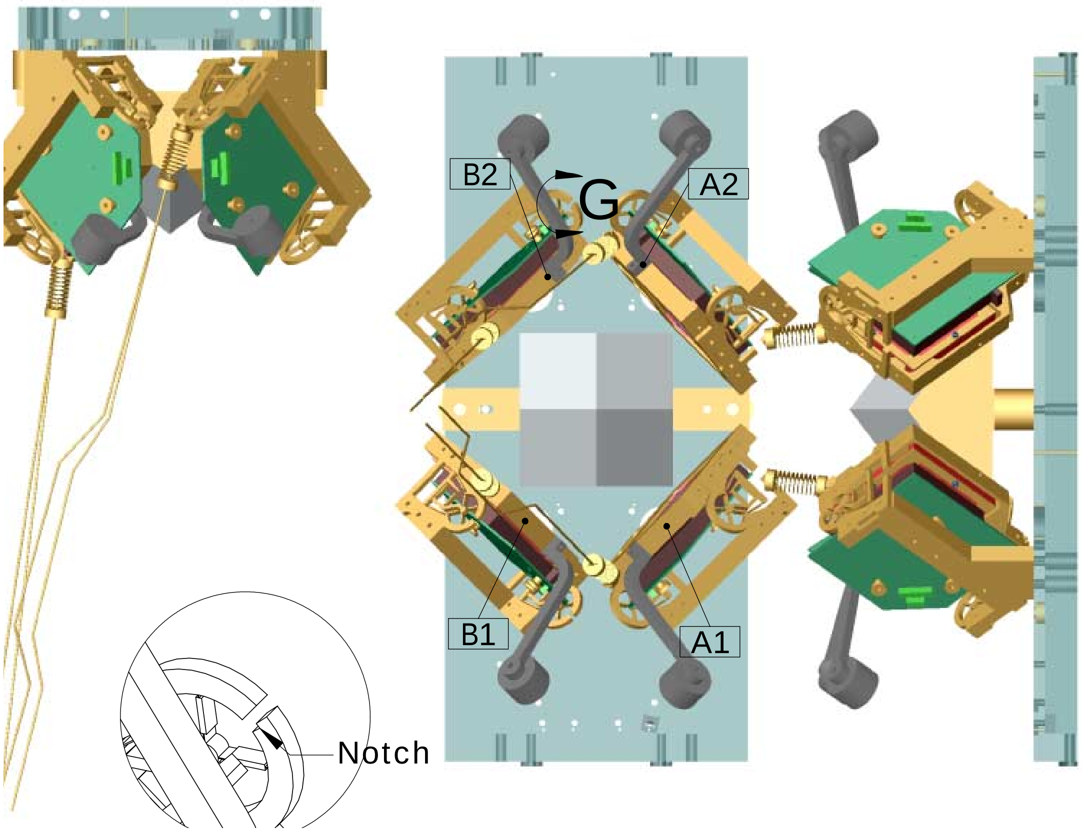

Figure 2: 4 eye shown for the wide field configuration. The top of the instrument is at the top for the center and right panels. The magnified detailed view shows the notch on the axles for the B detectors. The rotation axis, which points up before the mirror, points NW, NE, NE, and NW for the A2, B2, A1, and B1 detectors, respectively, after reflection. The rotation is right-handed for the wide-field configuration and left-handed for the high-res configuration.

2 Design

2.1 Requirements

To move the eye to the stop requires 0.018 N-m.[2] To move to the wide-field configuration, the rotation is right-handed where the rotation axis points out of the paper in the central panel of Figure 2. The rotation angle is about $\pm 4.3^\circ$ from the torque-free position of the eye.

The existing mechanism for inserting the wide-field camera mirror is to be used to move the eyes. The mechanism for the wide-field camera mirror turns $\pm 45^\circ$.

2.2 Design concept

For each eye, there is a drive shaft from the mechanism for the wide-field camera mirror to the eye. Since the rotation axes for the two ends of the drive shaft are not colinear, there is a flexure at each end of the drive shaft.

The flexures are made by Helical Products Company of Santa Maria, CA (heli-cal.com). The part number is 9227-8-8. See Figure 7.

The drive shafts are made of $\phi 1.5$-mm ASTM-A228 steel wire, which is commonly called "music wire." It has a very high tensile strength, 2.8 GPa.[3]

The drive has little friction and no backlash. Since the flexures are made of a single piece of stainless steel, they bend and turn without backlash. There are no parts with either sliding or rolling friction.

2.3 Position of the drive shaft

The rotation axes on the two A eyes, the ones on the right in Figure 2 are not accessible, because they are near a fold mirror. Therefore the flexure attaches on the eye at a point that is offset from the rotation axis.

At the driving end, the four flexures are offset from the rotation axis by ϕ26 mm, so that they do not collide.

[2]The measured torque is 0.036 N-m (Baker, D., Notebook "10/21/05", entry of 31 May 2006, p. 63) with heat straps made of four layers of 5-mil copper foil. With ten layers of 2-mil foil, the torque is 0.018 N-m.

[3]matweb.com

2.4 Flexures & drive shaft

The parameters of the drive shaft and flexures are in Table 1.

Parameter	*A eyes*	*B eyes*
Bend at eye		
of connection	50	35 °
of flexure	5	3 °
Bend at driving end	12	9 °
Length	401	310 mm

Table 1: Parameters of the drive shaft & flexures for the wide-field configuration.

As the eyes move between the high-res and wide-field configurations, the length of the shaft changes (Fig. 3). The greatest change is 1.7 mm. Of course the actual length the shaft cannot change; instead the flexures stretch or compress. Each of the two flexures can stretch or compress by up to 2.5 mm.

The steel drive shaft lengthens by 0.35 mm compared with the aluminum cryo-optical box when cold. The flexures accomodate that change in length easily.

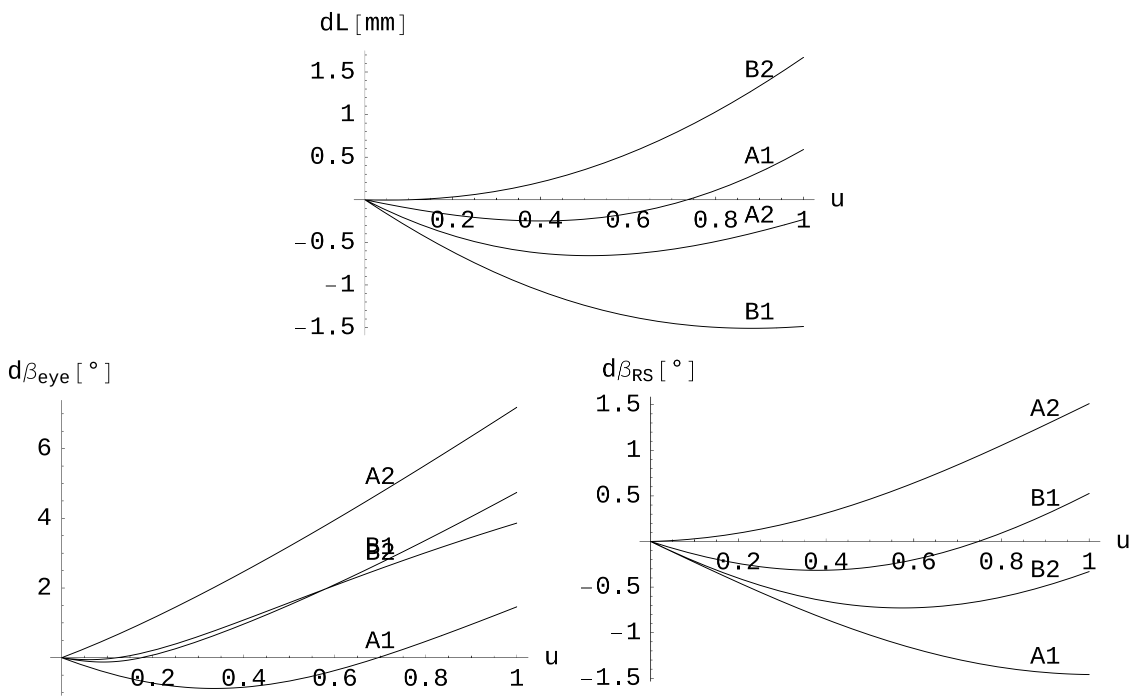

Figure 3: For the A and B eyes, changes dL in the length of the distance between the flexures (top), $d\beta_{\mathrm{eye}}$ in the bend angle of the flexure at the eye (bottom left), and $d\beta_{\mathrm{RS}}$ in the bend angle of the flexure at the rotation stage vs. rotation parameter u. The parameter $u = 0$ at the wide-field configuration, and $u = 1$ at the high-res configuration.

The drive shaft shifts 0.23mm due to gravity.

The restoring force of the flexures and the weight of the drive shaft & flexures make an oscillator with a frequency of 28Hz. The freq is much higher than anything of interest. The freq of the shipping container is 5Hz. A 5-g drop will move the drive shaft 1.2mm.

2.5 Reducing the rotation angle

The flexures, the drive shaft, and the eye act as four torsional springs in series to convert a $\pm 45^\circ$ rotation into one of $\pm 4.35^\circ$. Since the drive and rotation axes at the eye are bent at 50° for the A eyes and at 35° for the B eyes, the torque on the drive shaft is larger than the torque in the direction of the rotation axis of the eye by a factor of $\sec\theta$, which is 1.56 for the A eyes and 1.22 for the B eyes. The torsional spring constants are 110, 770, and 160 degree/N-m for the flexures, drive shaft, and the A eye, respectively. Since the four torsional springs are in series, the torque is the same at each spring. The flexures have little friction, since they are machined from a single piece of material. The same is true for the eyes. Therefore little torque is lost to friction. The two flexures twist 5°, and the shaft twists 30°. The eye rotates 4.35° and runs into a stop. For the A eyes, the torque is 0.051 N-m, which is a factor of 1.8 of that needed to just reach the stop. For the B eyes, the safety factor is 3.0.

Even though the torque is 3 times that needed to move the B eye, the torque, 0.06 N-m on the drive shaft, will not damage the Henein flexible bearing. When the bearing is at a stop, torque is converted to tension on its thin members, whereas it resists torque by bending of its thin members when it is not at a stop. A rough estimate of the maximum safe torque on the bearing is 2 N-m.

The torque is 0.7 of the maximum allowed for the flexures for an infinite number of cycles where the load reverses.[4]

The maximum shear stress in the drive shaft, 90 MPa, is a factor of 9 less than the allowable shear stress for ASTM-A228 steel. To derive the allowable shear stress, we scaled the “allowable” shear stress for steel, 90 MPa,[5] by the tensile strengths of ASTM-A228 and common steel.

[4] Williams, M., 2007, Helical Products Company, private communication. The maximum allowed torque is 0.044 N-m, where the flexure runs an infinite number of reversing cycles and the bend angle is 90°. The allowable stress is allocated to bending, torque, and translational misalignment of the flexure. We estimate that the maximum allowed torque is larger by a factor of 1.8 for our case where the bend angle is 12° and the translational misalignment is small.

[5] Popov, E., 1968, *Introduction to the mechanics of solids*, Prentice Hall, Englewood Cliffs, p. 554.

2.6 Interference with light path

The drive shafts for the A eyes are kinked by 19 mm to avoid blocking the light (Figure 4). Each drive shaft is in a plane when its rotation is at the mid point between the wide-field and high-res configurations (called the neutral position). At the wide-field and high-res configurations, the drive shaft is not confined to a plane because the driven end (at the eye) is rotated less than the driving end. In the neutral position, the kink in the A1 drive shafts is at 7:00 o'clock in Figure 2, and kink in the A2 drive shafts is at 11:00 o'clock.

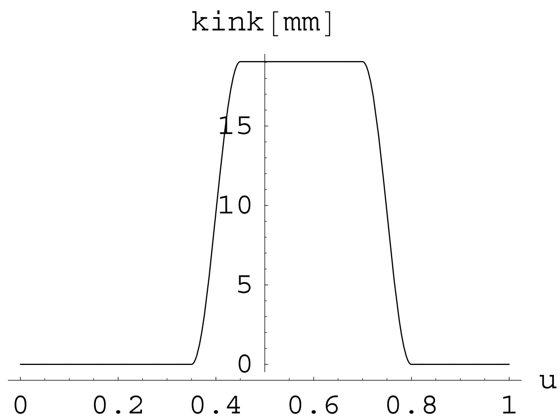

Figure 4: The kink in the A drive shafts as a function of the shaft parameter u, which is 0 at the eye and 1 at the other end.

To test whether the drive shafts interfere with the light beam and with each other, we computed the location of the drive shafts and the region covered by light rays as a function of the shaft parameter u. The parameter $u = 0$ at the end of the shaft at the eye, and $u = 1$ at the other end.

Figure 5 shows the drive shaft for the A1 and B1 eyes and the region covered by light rays for several values of the shaft parameter u. Near the eyes ($u = 0$), the drive shafts are well below the lit region. At $u = 0.8$ near the rotation stage, the drive shafts are well to the right of the lit region. In between, the shafts move up and to the right as u increases. The A shafts, were they not kinked, would block some light for $u \approx 0.6$.

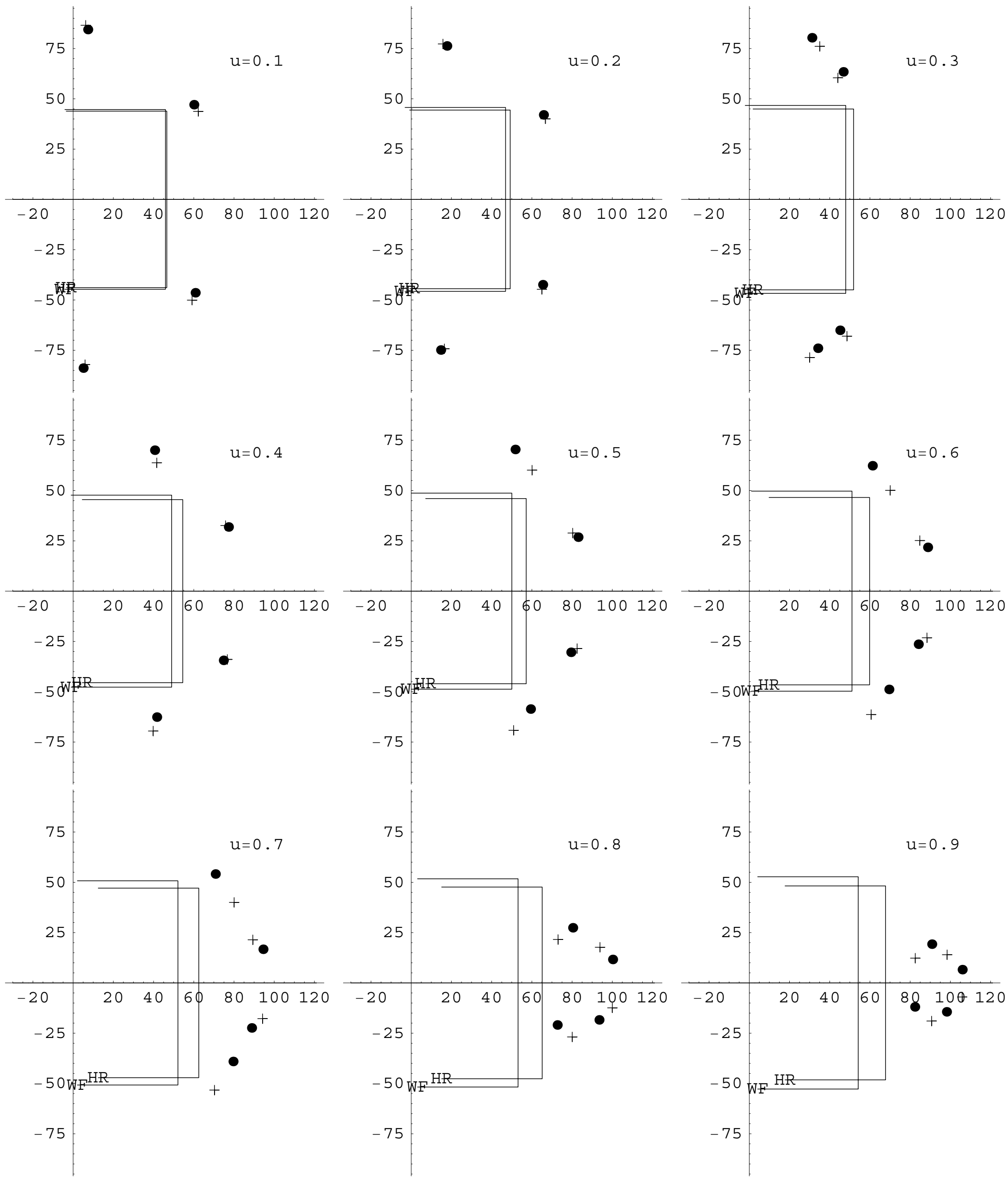

Figure 5: Drive shaft at the wide-field (point) and high-res (+) configurations and the region covered by light rays, the lower, right boundary of which is shown, for several values of the drive parameter u. The drive parameter $u = 0$ at the end of the A1 drive shaft near the eye, the driven end, and $u = 1$ at the driving end of the A1 shaft. The regions of light rays are labeled 'WF' for wide-field and 'HR' for high-res.

2.7 Imbalance

The added weight of the flexure and drive shaft unbalances the eye. As shown in Figure 6, the unbalanced torque is at most 9% of the torque needed to move the A eye and 15% for the B eye.

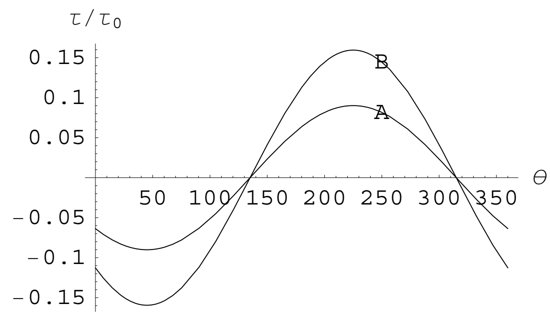

Figure 6: Torque due to the weight of the flexure and drive shaft compared with the torque needed to move the eye as a function of the instrument orientation.

3 Appendix: Flexures

An issue is whether the flexures (Figure 7) at the ends of the drive shafts will twist when a torque is applied. We derive the maximum torque allowed without significant twist and verify that experimentally with the 9227-8-8 flexures.

A flexure, bent by angle θ, connects a drive shaft to a load. The load resists torques perpendicular to its rotation axis, since it is on a bearing. Torque τ_{drive} is applied on the drive shaft.

Suppose the flexure transmits τ_{drive} to the load. Then the net torque on the flexure parallel and perpendicular to the rotation axis of the load is

$$(\tau_{\text{par}}, \tau_{\text{perp}}) = (\tau_{\text{drive}}(1 - \cos\theta), \tau_{\text{drive}} \sin\theta + \tau_{\text{load,perp}}).$$

The bearings on the load provide $\tau_{\text{load,perp}}$ to balance the net torque perpendicular to the rotation axis.

To balance the torque τ_{par} requires a force F, which is applied perpendicular to the bending plane with a moment arm R. If the force is applied at the end of the flexure, $R = L(1 - \cos\theta)/\theta$, where L is the length of the flexure.

Consider two cases: (1) the driving end is supported by a bearing and (2) the driving end is not supported. If the driving end of the flexure is supported by a bearing, the torque transmitted to the load is indeed τ_{drive}, since the bearing provides the torque to balance τ_{par}. If the driving end is not supported, the torque transmitted to the load is $\tau_{\text{drive}}(1 - \cos\theta)$.

If the driving end of the flexure is not supported, the flexure itself must exert the force F. Since the flexure resists translation with a spring constant k, the driving end of the flexure moves by

$$y = \tau_{\text{par}}/R/k = \tau_{\text{drive}}\theta/(Lk).$$

The unbalanced torque τ_{par} can be absorbed by the flexure if the force causes the flexure to move less than the radius r. Therefore the maximum torque that the flexure can transmit without twisting is

$$\tau_{\text{drive,max}} = krL/\theta. \tag{1}$$

With the 9227-8-8 flexure, the maximum torque is 0.4, 0.13, and 0.07 N-m for bend angles 10, 30, and 55°, respectively. The torque needed to move the eye is 0.018 N-m.

Figure 7 shows the flexure with 0.07 N-m of torque, which is 4 times that needed to move the eyes. (At 0.07 N-m, the end of the wrench lifts up.) At a bend angle of 0°, the flexure does not twist. At a bend angle of 30°, the flexure twists slightly. At a bend angle of 50°, the flexure twists severely. These results are consistent with equation 1.

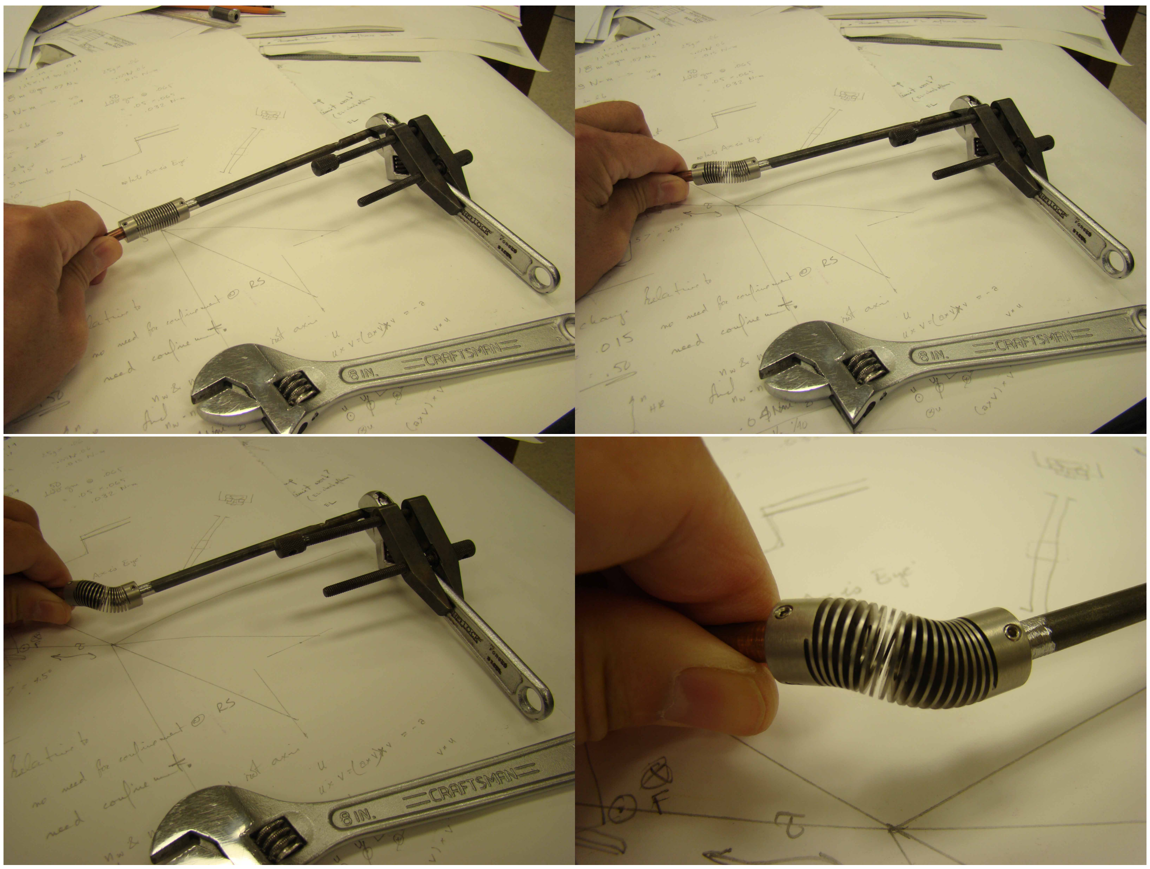

Figure 7: Twisting the flexure with a bend angle of 0° (top left panel), 30° (top right), and 60° (bottom). The applied torque is 0.07 N-m, which is 4 times that needed to move the eyes.

3.1 Support for the unclamped end of the flexures

For the A eyes, the unclamped end of the flexure at the eye moves significantly, since the the clamped end is offset from the rotation axis. Therefore the support on the unclamped end must be attached to the eye. In that case, the torque on the drive shaft τ_{drive} and the torque at the clamped end parallel to the rotation axis are related by

$$\tau_{\text{par}} = \tau_{\text{drive}} \cos\theta.$$

The torque on the drive shaft is 0.031 N-m, 1.74 times that needed to move the eye.

For the B eyes, the torque on the drive shaft is 0.021 N-m, 1.14 times that needed to move the eye.

For the flexures at the rotation stage, the maximum allowed torque is 0.4 N-m. Since that is much larger than the actual torque, twist is not significant, and the flexure may be unsupported.

For the flexures at the B eyes, the maximum allowed torque is 0.13 N-m. Since that is much larger than the actual torque, twist is not significant, and the flexure may be unsupported.

For the flexures at the A eyes, the maximum allowed torque is 0.07 N-m, which is 3 times the actual torque. Twisting shifts the free end 1/3 of the radius of the flexure. The need for a support is ambiguous.

3.2 Tilting the flexures

To avoid the problem of twisting altogether, the clamped end of the flexures at the eyes will be tilted so that the bend angle of the flexure is small. The tilt accounts for most of the change in direction between drive shaft and the rotation axis of the eye. As the eye rotates, the flexure bends a few degrees. The twist becomes insignificant.