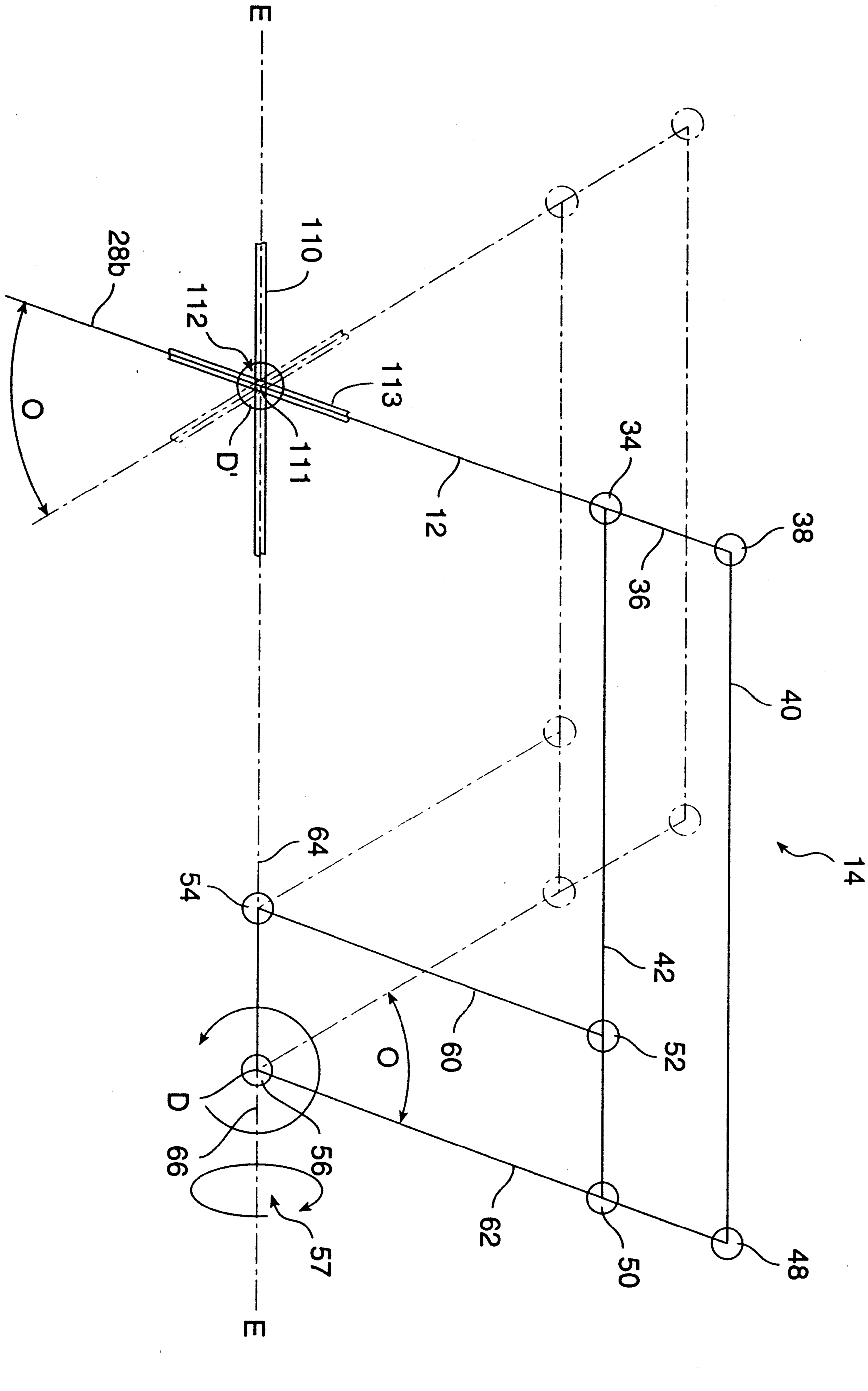

Figure 5-4: The remote center kinematics are formed by two coupled parallelagrams. 110 represents the body wall, and 111 is the remote center. The remote center maintains the same relation with points 34 and 38 as does point 56 with points 50 and 48, and need not lie along a line.

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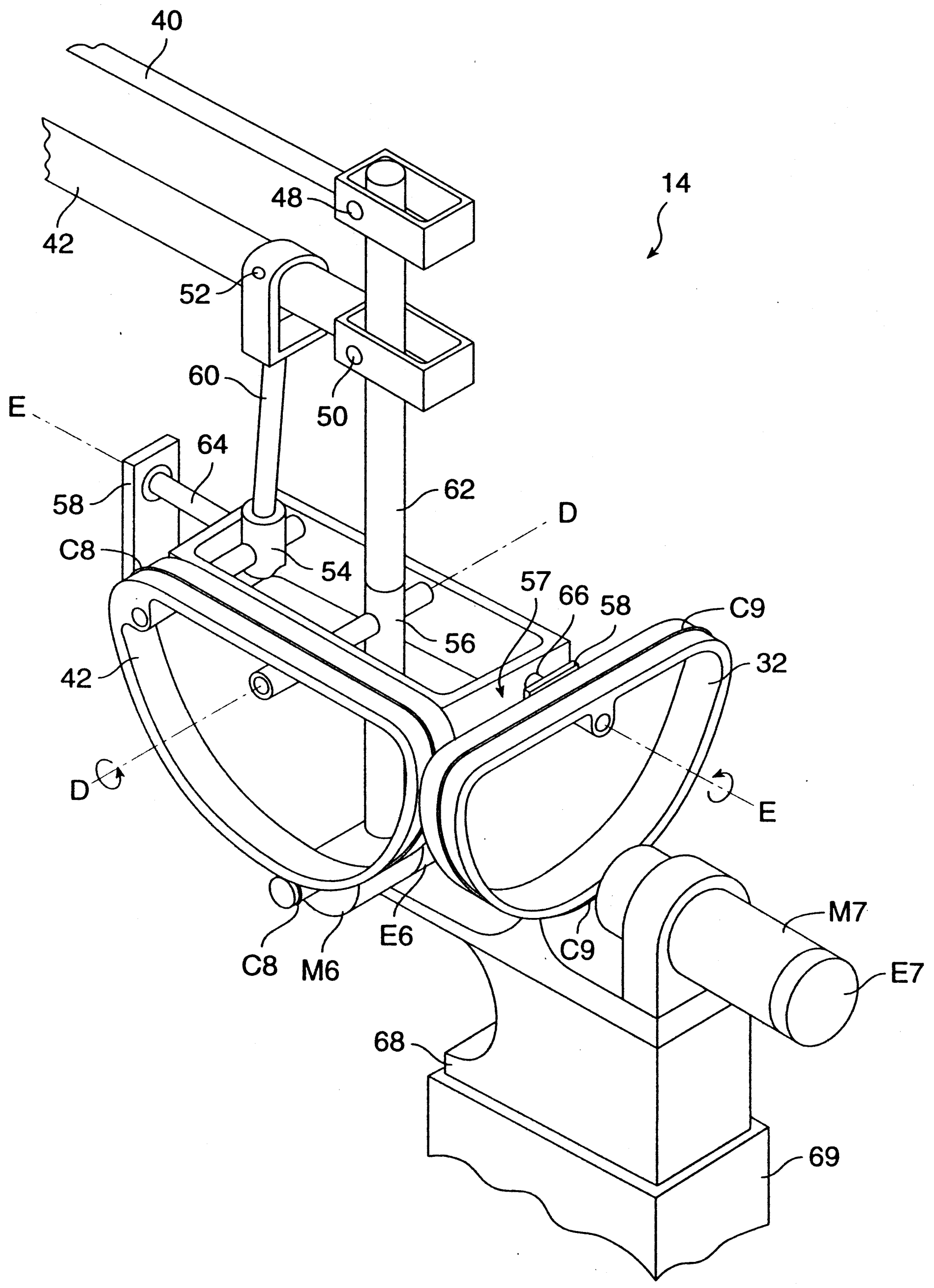

Figure 5-5: The two base positioner axes are both driven by backlash-free cable drives.

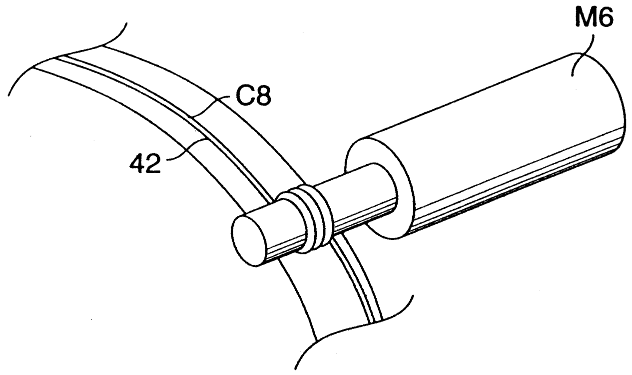

Figure 5-6: Cable drive used to drive a ring

5.2.1.3 Spring Counter Balance

In practice, weight imbalance can be compensted for using an active gravity compensation, or by using a spring counterbalance. We describe a spring counterbalance incorporated into the Silver Falcon below.

Figure 5-7 shows a schematic of the counterbalance. A cable is attached to a point on the bottom of member 56 beneath motor 6. This cable passes through a teflon bushing in the base support member 68, around two idler pulleys which are fixed to this base and to a spring whos opposite end is also fixed to the base. Angular motion of the parallelagram linkage about either axis D or axis E draws out cable and causes a deflection in the spring.

Let Δ_0 be the initial spring deflection, and Δ be the deflection above this amount due to motion of the two base axes. Also, let R be the radius at which the cable is attached to the member 56, let θ be the angular deflection of the member 56, let L be the length from this point to the teflon bushing when the θ is equal to zero, let d be this distance when θ is non-zero, and let α equal the angle between the cable and member 56. Then using the law of cosines and sines:

$$d = \sqrt{(R^2 + (R+L)^2 - 2R(R+L)\cos\theta} \quad (5.1)$$

$$\sin\alpha = \sin\theta\left(\frac{R+L}{d}\right) \quad (5.2)$$

$$\tau_{spring} = k(\Delta + \Delta_0)R\sin\alpha \quad (5.3)$$

$$(5.4)$$

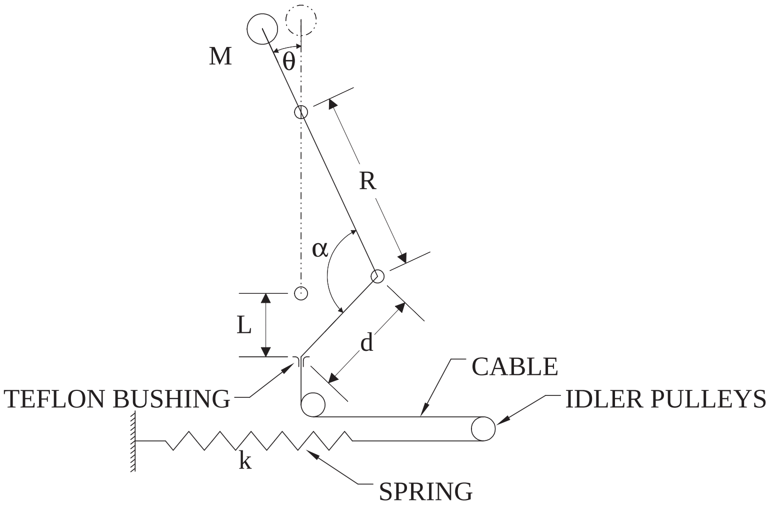

Figure 5-7: The spring counterbalance approximately balances gravity imbalance torques.

The gravity torque is proportional to the sin of the angle of deflection:

$$\tau_{gravity} = K \sin\theta \tag{5.5}$$

We measured the following values:

$$\begin{aligned} k &= 111 \text{ N/m} \\ K_{bottom} &= 1.9 \\ K_{top} &= 2.1 \\ L &= 0.025 \text{ m} \\ R &= 0.121 \text{ m} \\ \Delta_0 &= 0.038 \text{ m} \end{aligned}$$

where K_{bottom} applies when joint 2 is in its bottom position and K_{top} applies when joint 2 is in its top position.

Figure 5-8 shows all three torques as a function of θ, given in radians. This graph corresponds well with what we feel. The spring is slightly strong for the bottom position of joint 2, but feels better when joint 2 is in its top position. In either case, the error is within the friction in the base actuators so that it does not move when displaced.