Risley Prism Beam Pointer

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ABSTRACT

Ball Aerospace & Technologies Corp. (Ball Aerospace) has developed a Risley Beam Pointer (RBP) mechanism capable of high pointing accuracy and operational bandwidth. The prisms offer a wide field of regard (FOR) and can be manufactured and operated with diffraction-limited optical quality. The unit is capable of steering a 4-in. diameter beam over a 72° half angle cone with better than 100 µrad precision. Absolute accuracy of the beamsteering is in the range of 100 µrad to 1 mrad, depending on the thermal environment of the system. The system has demonstrated a control bandwidth of 23 Hz and better than 10 deg/sec of smooth target tracking anywhere within the FOR.

Keywords: Risley prism, optical tracking, optical beamsteering

1. INTRODUCTION

Risley prisms are pairs of wedge prisms that can be used to continuously scan an optical beam of a moderately large aperture over a wide angular range. They are particularly useful in conformal applications such as coarse beam steering from aircraft. They scan by purely mechanical (rotational) means. Steering with these prisms is inherently nonlinear in the sense that deflection is described by sines and cosines of angles of the wedge orientation. The use of Risley prisms is conceptually quite simple, but complexity exists in the mechanical designs and control algorithms.

The classical Risley prism pair has two identical prisms of index n. The pair can be used to direct a laser beam into any elevation angle θ and azimuthal angle ϕ, limited only by the prism wedge angle α. Given an azimuthal rotation ϕ' between the prisms as illustrated in **Figure 1**, it can be shown that for normal beam incidence, the direction cosines $\mathbf{k}_3$ of the directed beam are given by:

$$\begin{bmatrix} k_{3x} \\ k_{3y} \\ k_{3z} \end{bmatrix} = \begin{bmatrix} \cos\phi\sin\theta \\ \sin\phi\sin\theta \\ \cos\theta \end{bmatrix} = \begin{bmatrix} \beta\sin\alpha + \cos\phi'\sin\alpha\left[\sqrt{1-n^2+\gamma^2(\phi')} - \gamma(\phi')\right] \\ \sin\phi'\sin\alpha\left[\sqrt{1-n^2+\gamma^2(\phi')} - \gamma(\phi')\right] \\ (1+\beta\cos\alpha) + \cos\alpha\left[\sqrt{1-n^2+\gamma^2(\phi')} - \gamma(\phi')\right] \end{bmatrix} \tag{1}$$

$$\beta = \sqrt{n^2 - \sin^2\alpha} - \cos\alpha$$
$$\gamma(\phi') = \cos\alpha + \beta\left(\cos^2\alpha + \cos\phi'\sin^2\alpha\right)$$

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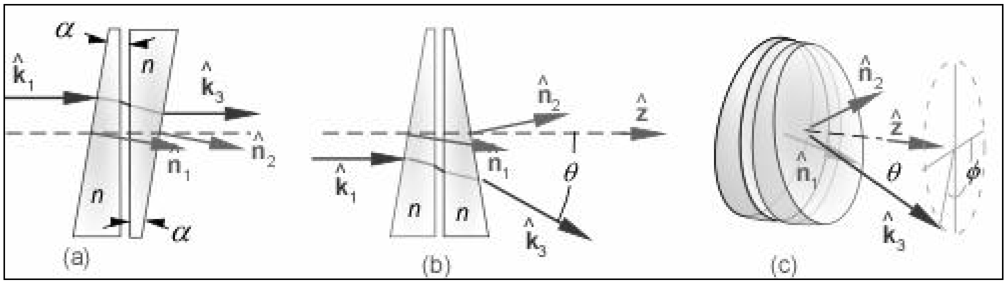

Figure 1. An ideal Risley prism pair with identical wedge angles and indices of refraction shown (a) with the wedge normals **n** aligned ($\phi' = 0^o$). The direction cosine **k** of the beam is offset, but undeflected at this orientation. (b) With wedge normals pointing opposite each other ($\phi' = 180^o$), the beam has maximum elevation deviation. (c) A perspective view. Note that the azimuthal angle ϕ' is swept out by co-rotation of the prism pair (dashed line).

These formulae give the direction cosines in terms of prism orientation. We require the inverse, so that, given the target elevation and azimuthal angles, one obtains the required prism orientations. For a two-prism beam director there are always two possible prism orientations for the same target angles.

The Risley prism pair has numerous drawbacks as a beam director. (1) Singularity: the prism rotation speed requirements become excessive as target angles approach the boresight of the prisms. (2) Nonlinearity: the control equations are nonlinear and require local linearization algorithms or look-up tables to invert the equations and provide definitive prism orientations. (3) Tolerances: prism wedge angle tolerances, alignment, and environmental variations such as temperature and atmospheric pressure significantly alter the beam directivity. (4) Boresight blind spot: tolerances and thermal variations prevent "access" of shallow boresight angles. A Risley pair "misses" the boresight by anywhere from a few to a few hundred μrad.

To avoid both the singularity and the boresight blindspot, a third prism is incorporated. The third prism provides an additional degree of freedom to the Risley pair and "pushes" the boresight off-axis. Continuous orientation of this third prism allows tracking a target through the boresight. By adding a third prism, the Risley control equations no longer have two, but an infinite number of solutions for the same elevation and azimuth target angles.

2. OPTO-MECHANICAL DESIGN

2.1 Mechanical design

2.1.1. Design description

The function of the RBP requires that three wedges be accurately rotated to a known position. To achieve this, the mechanical system must have three independent drive systems with angular position sensors. The wedges must be mounted in a manner that will not induce strain beyond acceptable levels to maintain the optical surface figure required. **Figure 2** shows a cross-section view of the system with the main components identified.

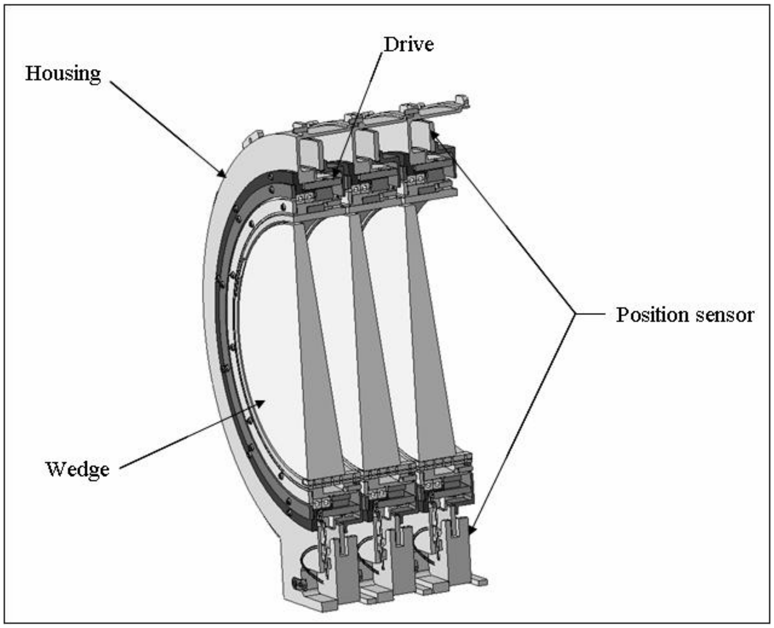

Figure 2. A cross-section of the RBP.

2.1.1.1 Mechanical drive

To drive the wedges a torque motor is used with the rotor being internal to the stator. The rotor is attached to a shaft joined to the housing using a set of back-to-back thin section duplex bearings. A compliant steel sleeve connects the outer bearing race to the aluminum housing, which allows for differential thermal growth between the housing and the shaft without altering the preload on the bearings. The bearings are preloaded and held in place using clamps as shown in **Figure 3**.

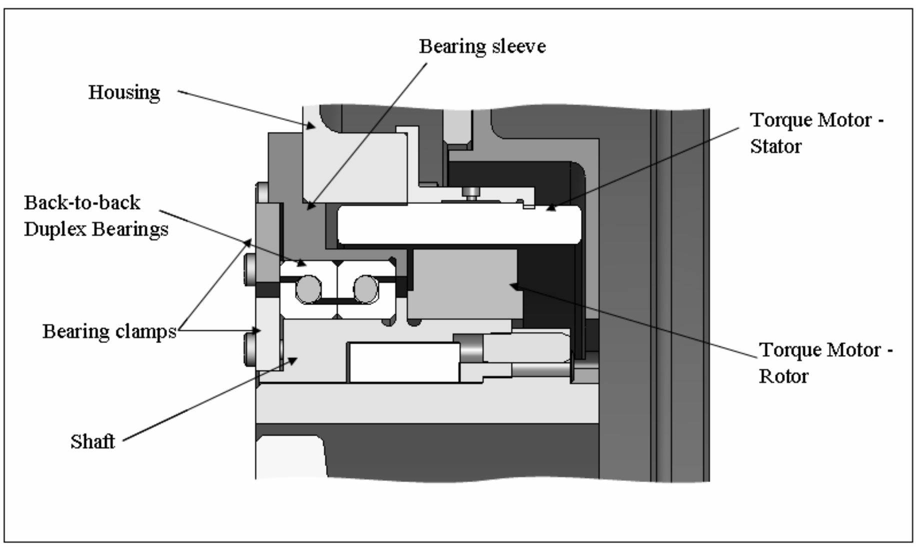

Figure 3. Section view illustrating the drive of the RBP.

2.1.1.2 Angular position sensing of the RBP

Accurately detecting the angular position of the wedges is a key design driver for the RBP system. The primary options that were considered for the sensors in this application were resolvers and rotary optical encoders. Ball Aerospace has heritage successfully using resolvers as position sensors for drives; however, resolvers require power to be supplied to the stationary and rotary components. As the RBP wedges need to rotate continuously, a transformer would be required to provide power to the rotating components. Implementing a transformer requires additional axial spacing between the wedges, which decreases the FOR. Resolvers also increase the inertia of the system, and although the current motor has sufficient torque to overcome the increase in inertia, more power would be required to operate within the same specification. A rotary optical encoder consists of a rotating disc and a stationary detector that senses angular position of the disc. An optical encoder can be significantly lighter than a resolver and does not require power to the rotating component. This makes the optical encoder the preferred position detector for this application. An absolute encoder was chosen over incremental models, allowing the system to be power cycled without having to re-zero the encoder position.

Figure 4 shows how the optical encoder is implemented within the assembly. The glass disc mounts to a custom hub that interfaces to the rotating shaft. The encoder read-station is connected to the housing using two precision pins; the relative position between the disc and the read-station is critically aligned using a microscope.

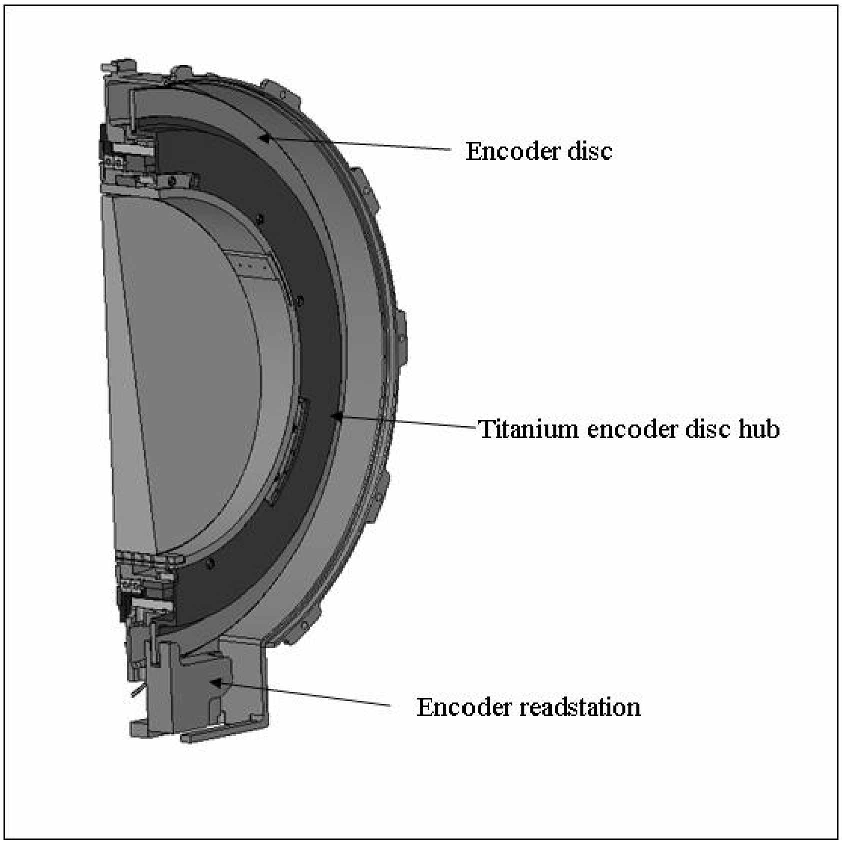

Figure 4. Position sensor for the RBP.

2.1.1.3 Interface of the optical elements

The operational thermal environment for the design is -50 to 70 °C. Between the rotating shaft and the optics there is a difference in the coefficients of thermal expansion (CTE). Thus, the optic must be attached to the shaft in a way that allows for this differential thermal growth without over- stressing the optic.

The design accommodates thermal expansion and contraction of the optic and bezel using tangential flexures that attach in three places, shown in **Figure 5**. The optic is bonded into a bezel which is then interfaced to the rotating shaft. The use of an intermediate bezel allowed the optic to be removed from the assembly during initial testing to protect it from possible damage. A side effect of the flexure mount is a loss of system stiffness, and thus the flexure design was optimized to give adequate radial compliance while remaining stiff axially. The flexure was analyzed using a finite element model. The results indicate that we achieved a successful balance between relief of thermo-elastic stress and maintenance of a high first fundamental frequency (~500 Hz).

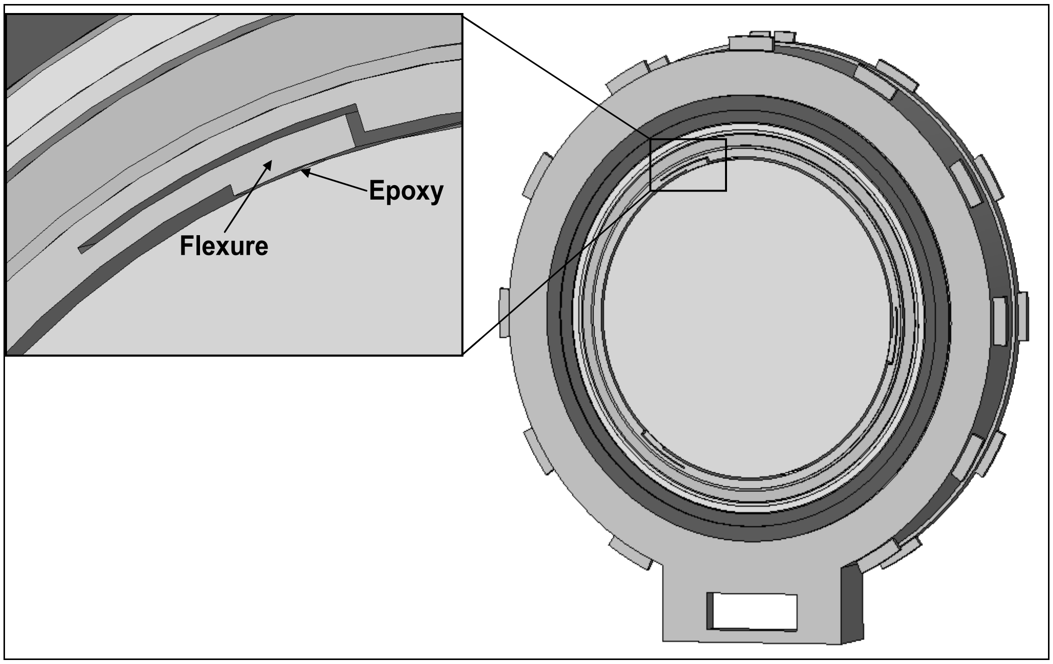

Figure 5. A single prism section highlighting the bond between the optic and bezel.

2.2 Optical design

The optical design of the RBP included analysis of polarization-dependent transmission, wavefront quality, stray-light, and astigmatism (anamorphic magnification). Three transparent prisms are used in the current design. The wedge angle is 7°, and the operating wavelength is nominally 1550 nm. In the current design, deflection angles greater than 60° are achieved, while maintaining diffraction-limited wavefront quality and over 75% polarization-insensitive transmission. At such large angles of incidence and using materials with a high index of refraction, the prisms must be coated to avoid high Fresnel reflection losses at the air-silicon interfaces. This coating will maximize throughput, but will also introduce phase changes to the transmitted light. In a system that relies on a specific polarization state, these phase changes must be accounted for. The theoretical coating reflectance curves for transverse electric and transverse magnetic polarizations are shown in **Figure 6**.

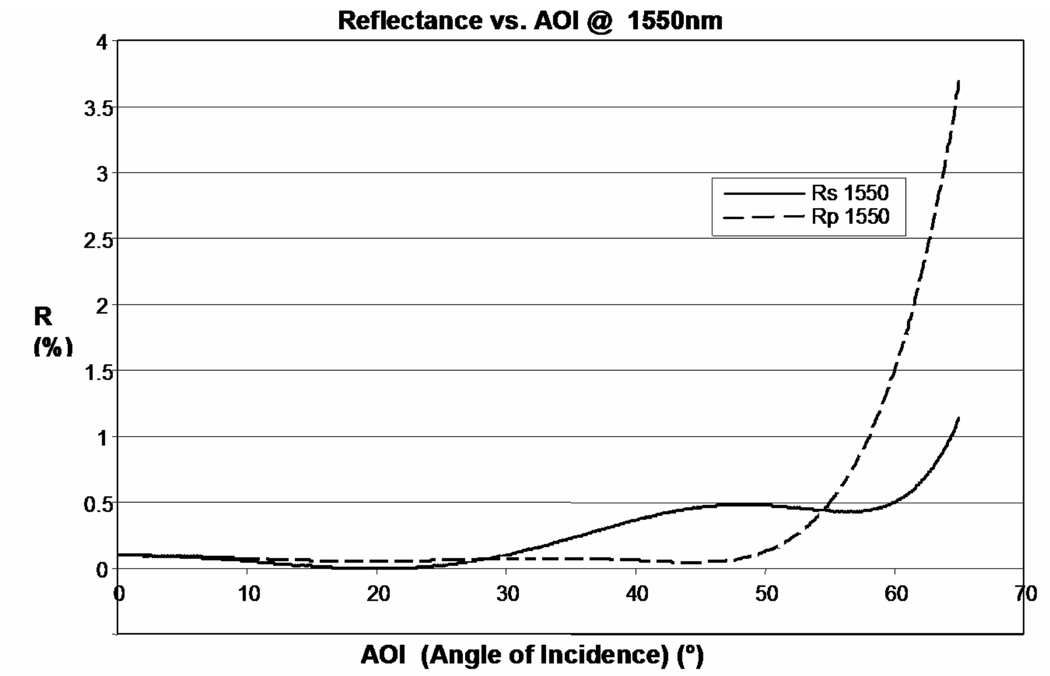

Figure 6. Reflection coefficients for silicon prism coating.

The AR coating is a proprietary prescription specifically developed for this RBP hardware. As shown, the coating successfully limits reflectance to a few percent all the way out to incident angles of 60º. The phase retardance of the coatings can also be calculated, and analysis predicts that the coatings do not appreciably distort the polarization state.

Another design consideration related to the throughput of the RBP is vignetting. Each prism deflects a light ray about 15°. At such large angles, the center of the optical axis translates appreciably as it propagates through the RBP. The prism thicknesses, orientations, and spacing in the bezel were all optimized to minimize the translation of the optical path and size of the optics. This trade was restricted by the wavefront distortion requirement. Though one would like to make the optics thinner to minimize the beam walk, increasing the diameter/thickness ratio would have compromised the beam quality. The total thickness of the RBP optical path is <6", and the beam translates < 2" at the maximum deflection angles.

As mentioned above, the wavefront quality of the RBP was a significant concern. It is worth reiterating here that this concern is one of the driving motivations for the use of a RBP on aircraft. The conformal nature of the beam director generates less air turbulence and theoretically, should thus maintain higher overall wavefront quality than systems where the beam pointer protrudes into the airstream. The need for high wavefront quality imposes a stringent requirement on the surface figure of the wedge prisms used. The high index of refraction of the optic helps increase the deflection angle of the system, but it also magnifies the transmitted wavefront error. With six air to surface transitions, the wavefront error can accumulate quickly. Six wedge prisms have been manufactured by Coastal Optical Systems, and the surface figure error at 1550 nm was less than $\lambda/50$ rms for each, with the latest wedge figured to better than $\lambda/200$ rms. The surface figure error includes power and did not change significantly after bonding the optics in their bezels. The transmitted wavefront error of a full, three-prism assembly was measured at 1550 nm over a 4" clear aperture to be less than $\lambda/13$ rms for all pointing angles. Over a 2" clear aperture, the wavefront error is $<\lambda/20$ rms. The assembly thus maintains diffraction-limited performance throughout the field of regard.

Another issue considered while designing the system was retro-reflection from the prism faces. Even though the AR coatings reflect very little light, the detectors behind the RBP are generally very sensitive. Thus, reflection of the transmitted light back into the optical system was a concern. The RBP prisms are arranged so that during operation the outgoing light rays are never normally incident to any prism surface. By properly arranging the prism faces, one can ensure that this condition is satisfied in all but a finite number of relative prism orientations. One can then eliminate the occurrence of these specific combinations through proper design of the control law. Retro-reflection of the outgoing beam from the RBP was never observed during the integration and testing of the assembly.

The optical design of the RBP also included analysis of the anamorphic magnification introduced. The RBP unavoidably introduces unequal magnification to the beam being directed, as does any refractive beamsteering device with planar optics. This occurs because the light rays are refracted rather than reflected. The beam footprint, as viewed perpendicular to the beam propagation direction, is thus always a geometric projection of the beam at the other side of the planar interface. In the RBP system the beam is thus compressed or expanded in the direction of deflection. Pictures of the beam profile at various deflection angles are shown in **Figure 7**. The beam is distorted, but not vignetted.

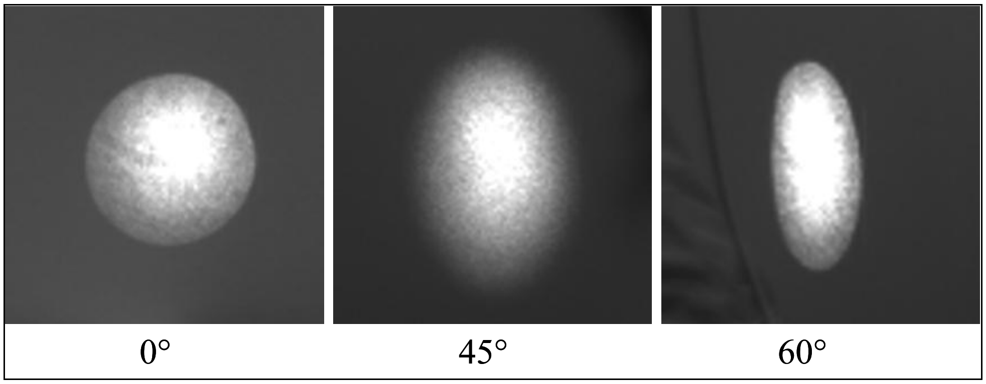

Figure 7. Transmitted beam profile at several deflection angles.

At 0° defection, the beam propagates without distortion. However, with 60° deflection, one can see that the rays are transversely compressed, and the beam footprint is compressed.

In a Risley beam pointing system the signal received at the distant terminal will decrease as the pointing angle increases because the diffraction-limited divergence is inversely related to the beam diameter. At 60°, the area of the transmit beam will be twice as large at the distant terminal, and the intensity reduced by 3 dB (50%), as compared to the signal at 0°. For the incoming beam to the Risley assembly, the opposite distortion will occur. The entire front surface of the prism assembly will be illuminated by the distant terminal. However, only an elliptical subaperture of the incident light will propagate past the circular aperture stop on the other side of the Risley assembly. Since the incoming beam is expanded in one dimension, the amount of light collected by the Risley assembly will decrease as the angle of incidence increases. The energy density of the incoming beam is uniform since it is coming from a distant source. The total power collected will then be proportional to the area of the admitted input aperture. Note that the uniform energy density also means that the beam profile admitted to the Risley assembly will always be uniform, and only the absolute intensity level will change. Thus, at 60°, the received power is one-half the signal received at 0°. As explained above, this phenomenon is notable because it is intrinsic to the use of refractive, planar optics in the RBP and cannot be compensated without additional optics inserted before or after the RBP.

A complete optical design and analysis was completed for the RBP. Optical performance was analyzed with respect to beam quality and throughput, polarization dependence, stray-light, and distortion. The final system matched well with the theoretical predictions, and the RBP system demonstrated is a high-performance and well-characterized optical component.

3. CONTROL LAWS AND SOFTWARE

3.1 Control laws

One of the difficulties with a three-Risley beamsteering system is controlling the prism rotations for acquisition and tracking. The addition of a third prism alleviates control difficulties that arise when trying to point or track at angles near the system boresight. However, the use of three prisms also creates complexity in the control law, as the system is under-constrained with only two target coordinates. The goal of the control laws is to resolve this ambiguity, while minimizing the motor speeds and accelerations. The control laws for the 3-element Risley prism beam pointer are described in detail elsewhere (see reference 1). The key features of the method are: The three prisms are subdivided into a single element called the Wedge Director (WD), and a coupled pair, called the Risley Pair (RP). The degrees of freedom of the system are reduced by choosing an appropriate functional definition of the WD orientation dependent on the target angle. The

RP positions are then solved for using the WD position and target angle. By choosing an appropriate function for the WD, the system performance can be optimized.

3.2 Software

The Risley control calculations are implemented in the C++ computer language. This software performs the calculations required by the control law as well as controlling the Risley prism motors. The software was written to execute on a Texas Instruments TMS320C6701 digital signal processor (DSP) unit, which includes an on-chip floating point processor and runs under the Texas Instruments DSP/BIOS real-time operating system.

The RP motors are direct-drive, two-phase, brushless dc motors with feedback provided by a 22-bit absolute position encoder. The commutation of the each motor's magnetic field generated by the coils is performed by software using position information from the encoder. The complete Risley calculations and motor control and commutation software run at 1 kHz. A block diagram of the software architecture and data flow is shown in **Figure 8**.

The first step in controlling the RP system is to perform the calculations to determine the desired position of each Risley motor. This software module is sent the desired azimuth and elevation angle to point the optical system and outputs the desired position for each of the three Risley prisms. The first task is to calculate the desired position of the first RP: the WD. This is a straightforward function of the target azimuth and elevation. This results in two possible positions for the WD; the one closest to the current position is chosen. As a final check, the WD total motion is evaluated and if found to be impractically large, is limited to a more realistic value.

With the first RP position known, the approximate position of the remaining RP is calculated using a simple geometric vector approximation. This initial guess is usually within a few degrees of the exact solution. Just as with the WD, two results are generated corresponding to mirror-image positions of the RP. The approximation that results in the smallest total movement from the current positions is used.

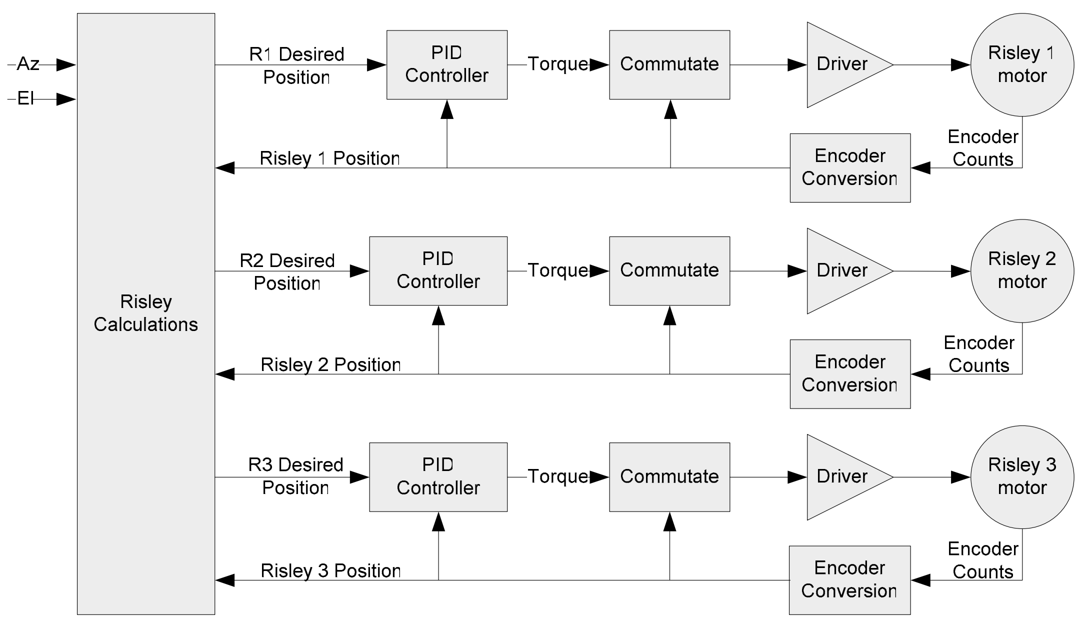

Figure 8. Block diagram of the RP control architecture and data flow.

The exact solution is calculated using an iterative algorithm seeded with the above approximation. The iterative algorithm uses Snell's law to determine the actual system pointing angle and then employs differentials to iterate to a closer solution. The algorithm terminates when the pointing angle is within a specified tolerance.

With the desired position for each prism known, a closed-loop control system is used to set the position of each Risley motor. The actual prism positions are obtained from the encoders and then subtracted from the desired prism positions to generate error signals. The error signals are used in a proportional-integral-derivative (PID) motion controller to calculate the dynamic torques to null the position errors.

The torque values are used by the commutation algorithm to calculate the phase and current values to energize each motor. The result is two amperage values going to each motors sin and cosine coils respectively. These amperage values are converted by the motor driver electronics into pulse width modulation signals and sent to the motor coils.

In addition to the Risley control calculations and motor control, the DSP is used as a system controller, communication processor, and to control two fast steering mirrors. Significant development went into optimizing the above algorithm to enable it to execute at the required 1 kHz rate. The exact processor loading is proprietary, but is only a fraction of the millisecond allowed.

4. HARDWARE DEMONSTRATION

Six Risley prism wedges have been manufactured, assembled, and tested. **Figure 9** is a picture of a single prism and a side view of three wedges assembled in series.

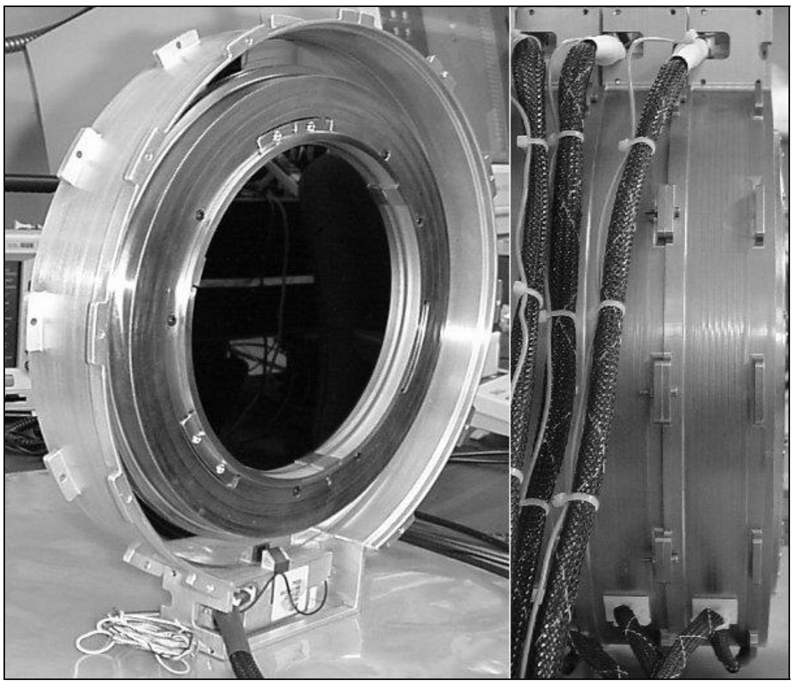

Figure 9. Single prism mechanism shown at left, side view of three-prism assembly shown on the right.

The RBP FOR, optical throughput, optical quality, pointing precision, and bandwidth were all tested and documented in a laboratory environment using a static laser source, linear position detector, and a motorized rotary mount. These characteristics of the RBP have also been confirmed in an environmental chamber as verification that the design can withstand thermal and vibration effects without performance degradation. The measured performance data are summarized in **Table 1**.

Table 1. Summary of performance parameters measured for the Risley beam pointer.

Parameter	Value	Design limitation
Field of regard	±72-deg half cone angle	Wedge angle and thickness (size, weight)
Pointing precision	100 μrad	Optical encoder resolution (22 bits)
Bandwidth	23 Hz	Mechanical slew rate and settling time
Optical throughput	85-96%	High refractive index for silicon needed for FOR leads to reflections
Optical quality	Diffraction limited	Optical surface figure on each wedge face

The motorized rotary mount was used to simulate 1-axis platform motion (i.e., aircraft roll, pitch, or yaw) and was programmed to slew at up to 10 deg/sec. The RBP was able to acquire and track an incoming signal up to the 10 deg/sec rate, successfully coupling the incoming beam into a fiber optic receiver with a 100 μrad field of view. Following the rotary table and laboratory testing of the RBP, the system was also tested within a 3-axis flight motion simulator (FMS) programmed with a typical flight pattern. The FMS demonstration was successful, and the RBP was validated as having the bandwidth and precision necessary to establish a link between an air platform and a suitable target.

5. CONCLUSION

Ball Aerospace has successfully developed and demonstrated a three-prism RBP capable of steering a 4-in. diameter beam over a 72° half angle cone with better than 100 μrad precision. The demonstrated system bandwidth is 23 Hz and up to 10 deg/sec of smooth target tracking anywhere within the FOR has been shown using a motorized mount and 3-axis flight motion simulator. The RBP can be used in various applications requiring coarse beam pointing or scanning.

REFERENCES

1. M. Sanchez, D. Gutow, "Control laws for the 3-element Risley prism optical beam pointer," *Free-Space laser communications VI*, to be published.