A FINE POINTING MECHANISM
FOR INTERSATELLITE LASER COMMUNICATION

Pablo Bandera

Moog, Inc., Schaeffer Magnetics Division
21339 Nordhoff St.
Chatsworth, CA 91311
Telephone: (818) 576-6804 / Fax: (818) 341-3884
E-mail: pbandera @sch.moog.com

ABSTRACT

The future of telecommunications depends largely on the development of free-space intersatellite laser communication. This technology in turn depends on a reliable way to direct a laser beam from one satellite to another, requiring extremely high pointing accuracy, low power, and sufficient bandwidth to reject satellite disturbances. Moog Inc., Schaeffer Magnetics Division, is developing a Fine Pointing Mechanism (FPM) to meet these demanding requirements. This miniature electromagnetic tip/tilt mechanism is more efficient and reliable than voice-coil-actuated devices and is capable of more travel than piezoelectric-actuated devices.

1. INTERSATELLITE LASER COMMUNICATION

The emerging technology of laser telecommunications will help make new satellite constellation designs feasible. In order for the technology itself to be feasible, however, a mirror-tilting device is needed to deflect the laser beam from one satellite to another. The distance between satellites may be several thousand kilometers. Pointing a beam at a mirror mounted on the nearest satellite, therefore, requires a positional accuracy on the order of 1 microradian. At the same time, this device must be capable of moving the mirror as much as +/-35,000 microradians (+/-2 degrees) to provide adequate coarse pointing around the neighboring satellite. The goal for power consumption was to achieve these 2 degrees of travel with 2 Watts.

The device must have sufficient bandwidth to reject satellite vibrations and disturbances. For small signal disturbances on the order of 0.01 degrees this bandwidth should be about 200 Hz. Larger disturbances of about 1 degree need to be rejected below 1 Hz.

Two types of devices are usually considered for actuation of the beam-steering mirror: voice-coils and piezoelectric actuators. The former offers a potentially large stroke for little power input, but is somewhat limited in bandwidth due to its low force output and consequently low stiffness. Piezoelectric actuators by contrast offer high bandwidth and stiffness, but provide very small position output even at relatively high voltages. The ideal device should combine the benefits of both technologies.

Figure 1. Fine Pointing Mechanism with mirror mounted on the moving platform.

2. FPM PRINCIPLE OF OPERATION

The Fine Pointing Mechanism (FPM) is a miniature tip/tilt device weighing 0.46 lbs and measuring 1.74”x1.58”. It is essentially a configuration of four identical electromagnetic circuits, positioned at 90 degrees from each other around the circumference of a circle (refer to figure 2). Four small permanent magnets are mounted to a moving mirror platform, while four corresponding coils and coil cores reside within a fixed housing. Consequently, most of the components are stationary.

Each circuit magnetically pulls on the mirror platform. However, by increasing positive current in one coil a magnetic field is generated which opposes that of the permanent magnet directly in front of it. Simultaneously increasing negative current in the coil 180 degrees away adds to the magnetic field in that circuit. In this way, a differential force is produced which tilts the mirror platform about its center. Similar operation of the other two coils produces motion along the orthogonal axis, so that the mirror can be positioned anywhere within an optical cone. The platform is mounted on a flexible BeCu diaphragm that provides a linear restoring torque in any direction against which the electromagnetic torque can react, yielding positional control. Also, by varying the total current in all four coils simultaneously, the platform can be positioned linearly along its centerline, providing an additional degree of freedom if desired.

The physical equations describing how the FPM works are fundamentally different from those of other designs which use voice coils. The torque is produced by varying the magnetic fields inside attractive airgaps, rather than inducing Lorentz forces on moving coils. While a voice coil requires relatively large magnets and thin coils, the FPM uses small magnets and large coils. The extra number of turns and larger wire size reduces power consumption, and smaller magnets are generally cheaper and easier to handle. Because the coils are stationary, there are no moving electrical connections, which greatly increases reliability. The coil cores are stationary as well, and the magnets move in front of the coils. This eliminates mechanical clearance problems associated with moving parts inside or around the coils, making the device generally easier to assemble and less expensive.

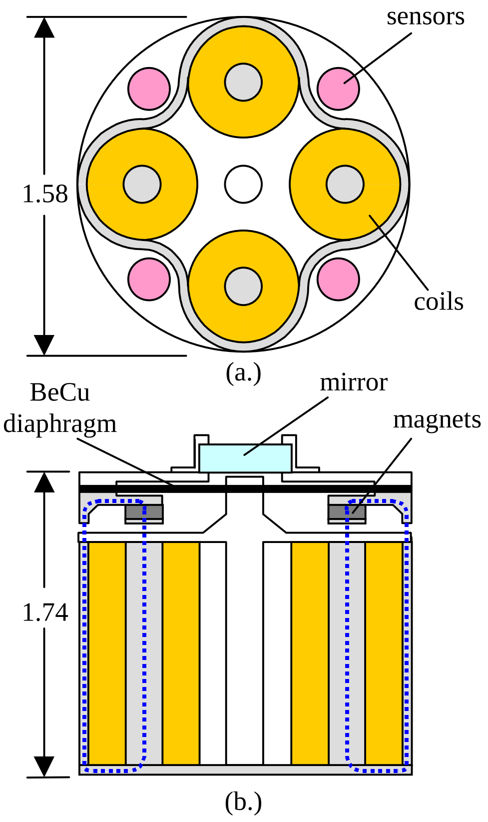


Figure 2. Cross-sectional views of the FPM looking (a.) down from the top and (b.) from the side.

Because the magnetic efficiency decreases significantly with increasing airgap length, the stroke of the FPM is more limited than that of a voice-coil-operated device. But it is significantly less limited than that of a piezoelectric actuator. Whereas piezoelectric devices may achieve strokes on the order of 0.5 degree with 100 Volts, the FPM can move 2 to 3 degrees with 15 Volts. Also, the linearity and drift issues involved with piezoelectrics do not exist for the FPM.

To achieve the high pointing accuracy required for intersatellite laser communication, non-contacting inductive position sensors are mounted between the coils to provide closed-loop feedback control. The FPM has only one moving part (the mirror platform) mounted on a frictionless flexure spring, and is inherently an infinite-resolution device. Therefore the position accuracy is primarily a function of the sensor error. Thermal distortion of the platform itself can be filtered out by using two matched sensors for each axis.

While there are four magnetic circuits in the FPM, each axis of motion is controlled by two coils simultaneously. These coils, in fact, can be physically wired together in series. The problem of controlling four channels then reduces to a simple matter of controlling two coil pairs, each one corresponding to an axis of motion. The closed-loop bandwidth and damping characteristics are tuned to the desired values using standard electronic compensation techniques.

3. MODELING

3.1 Magnetic Modeling

The magnetic design and analysis was done on Ansoft Magnet. 2-dimensional and 3-dimensional finite element models were created to check for magnetic saturation and evaluate torque. The magnetic flux in the circuit is a combination of the permanent magnet and coil fluxes, and these in turn are affected by the position of the mirror platform.

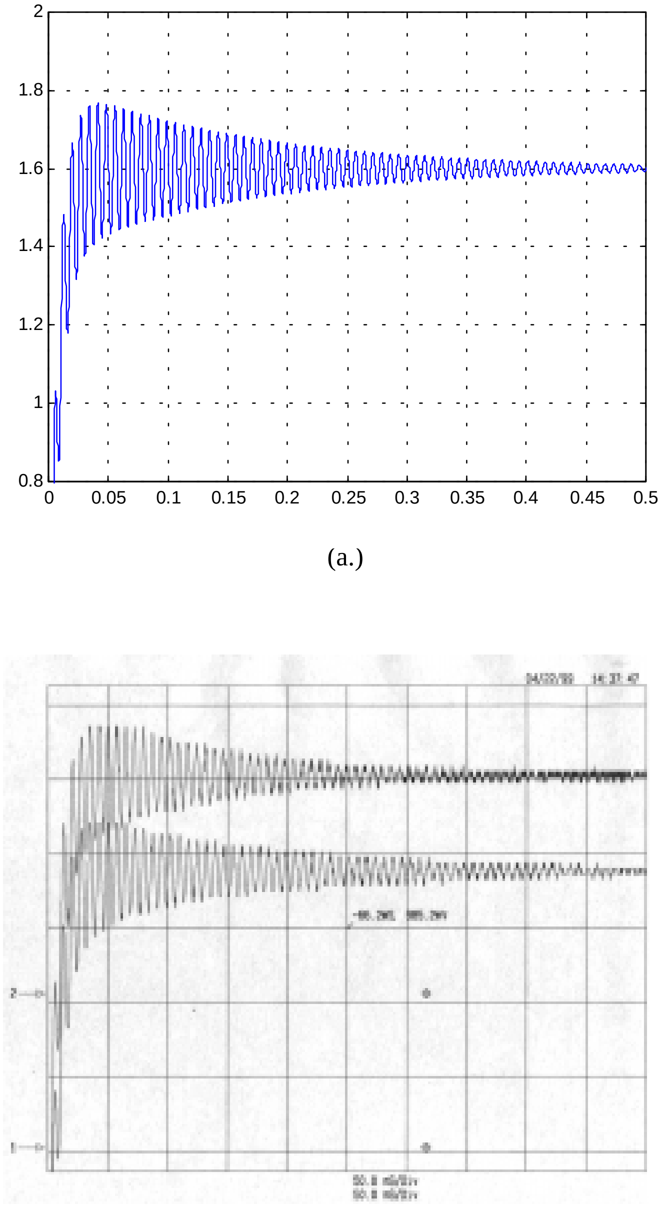
Motion is generated by increasing the flux density in one airgap while simultaneously decreasing it in the opposite airgap, creating a net torque, which equals…

$$T_{net} = T_{airgap1} - T_{airgap2}$$

It seems intuitive that in an electromagnetic design such as this, one should try to maximize the efficiency and consequently the flux in the entire circuit. But it is the *difference* in flux densities between opposite airgaps that creates torque. Increasing the flux in both airgaps keeps the net torque the same. The magnetic model was used to find the optimum configuration that would allow flux to be both increased and decreased efficiently.

3.2 Dynamic Modeling

The torque values obtained from the magnetic model, along with measurements made in the laboratory, were used to develop a dynamic model of the FPM on Matlab/Simulink. Figure 3 shows a comparison of the model to the actual hardware for an open loop step response. The extremely low damping evident in this figure was one of the more challenging features to deal with when closing the position feedback loop. Having an accurate model allowed various different control strategies to be tested before applying them to the FPM itself.



(a.)

(b.)

Figure 3. Comparison of (a.) simulated step response and (b.) actual step response (both x and y motions shown in second plot).

4. PERFORMANCE

4.1 Test Set-Up

The test data in this paper was taken using a dSPACE rapid prototyping system. This system converted a controller model created in Matlab to C code and used it to close the position feedback loop around the actual FPM prototype. In this way the real hardware could be tested very quickly and easily without having to assemble a breadboard controller or modify electronic components.

The open-loop natural frequency of the FPM is 140 Hz. It is believed that a 200 Hz closed-loop bandwidth for disturbance rejection will be easily achieved using classical feedback control techniques. However, due to computational time delays inherent in the dSPACE system, the highest frequency at which the hardware could be run was about 50 Hz. It was therefore not possible to run a closed-loop frequency response test beyond that frequency. An analog version of the controller is currently being built and will be available in the near future.

In the meantime, the more critical issues of power consumption and accuracy were addressed. Noncontacting inductive sensors were used to sense the angular position of the mirror platform. The position signal was saved in a Matlab .mat file using the dSPACE system, where it could be easily analyzed and displayed.

4.2 Power Consumption

The dissipated power of the FPM was measured by applying voltage directly to the coils in an open loop mode and plotting the square of this voltage divided by the DC resistance vs. angular position (see figure 4). The power is a direct function of the stiffness of the BeCu diaphragm: a stiffer diaphragm requires more power to deflect it. Figure 4 therefore shows that the stiffness in the x-direction and y-direction is almost identical. This is a result of using a single flexural member on which to mount the mirror platform.

When the position feedback loop is closed, any asymmetries in the stiffness or deflection of the mirror platform are essentially taken out because of the geometric relationship between the sensor axes and the axes of motion. From figure 2(a) one can see that the sensor axes are rotated 45 degrees with respect to the coil axes (which correspond to the x and y motions of the mirror platform). Consequently, a coordinate transformation is required so that the feedback signals are proportional to the x and y motions defined by the coils. This transformation has the following form…

$$X_{\text{feedback}} = \frac{1}{\sqrt{2}} \left(X_{\text{sensor}} - Y_{\text{sensor}}\right)$$

$$Y_{\text{feedback}} = \frac{1}{\sqrt{2}} \left(X_{\text{sensor}} + Y_{\text{sensor}}\right)$$

Each feedback signal is a function of both the x and y sensor outputs. Any difference between these outputs, due to factors such as asymmetric diaphragm stiffness or offsets, affects both x and y feedback in the same way. The closed-loop feedback signals, therefore, are always symmetrical.

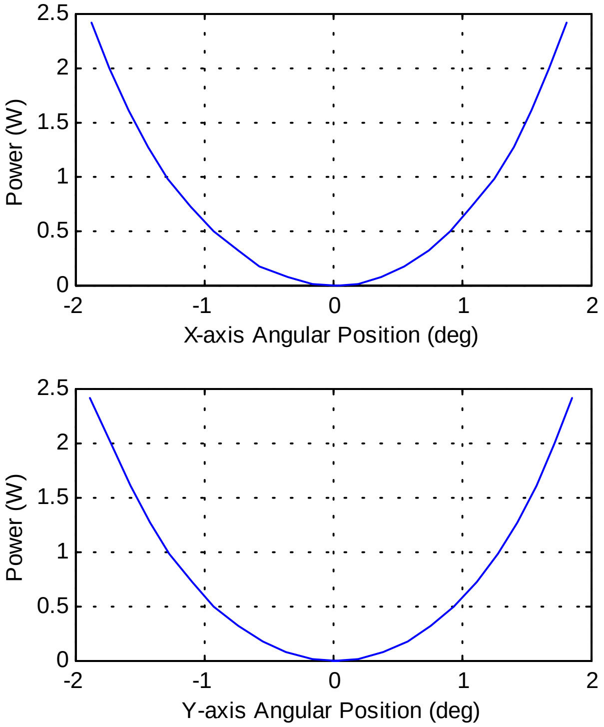


Figure 4. Power consumption vs. angular position in the x- and y-directions.

4.3 Step Response and Accuracy

Figure 5 shows a series of +/-1-degree step responses commanded simultaneously to the x- and y-axes. The dotted line is the commanded input, and the solid line is the feedback signal in degrees. While the rise time is slower than desired for the reasons described in section 3.1, the stability and damping characteristics are well within specifications. There is effectively no overshoot or oscillation due to the mechanical characteristics of the FPM. There are, however, small random oscillations due to electronic noise in the test set-up and sensor wiring.

A close-up of the position signal, plotted in figure 6, shows this noise more clearly. The average or RMS value of the signal is essentially that of the command, which suggests that the physical error between the actual and the commanded position is close to zero. However, the position signal itself varies within a maximum range of +/-.002 degrees, or +/-35 microradians. To achieve the goal of +/-1 microradian accuracy, future electronic set-ups should have better shielding so that true position error can be distinguished from electronic noise.

4.4 Cross-Axis Coupling

Ideally, the x- and y-axis motions of the mirror platform should be mechanically independent of each other, so that motion in one axis is a function of the command to that axis only. To test this, the FPM was cycled between +/-2 degrees at 0.5 Hz in the x-axis, while the y-axis was not commanded at all. The y-axis was then cycled with the x-axis not commanded.

Figure 7 shows that there is indeed some coupling between the two axes. For this test, a maximum deflection of 26 to 30 microradians resulted from cycling at 0.5 Hz. Cycling at a lower frequency would have allowed the feedback loop to reduce the error and hold the uncommanded position closer to zero, but some coupling does nonetheless exist. The deflection amplitude is within the noise amplitude discussed in section 3.3, which suggests that it should have little effect on positional accuracy as measured on the current test set-up. However, as we approach the desired accuracy of +/-1 microradian, this coupling should be minimized.

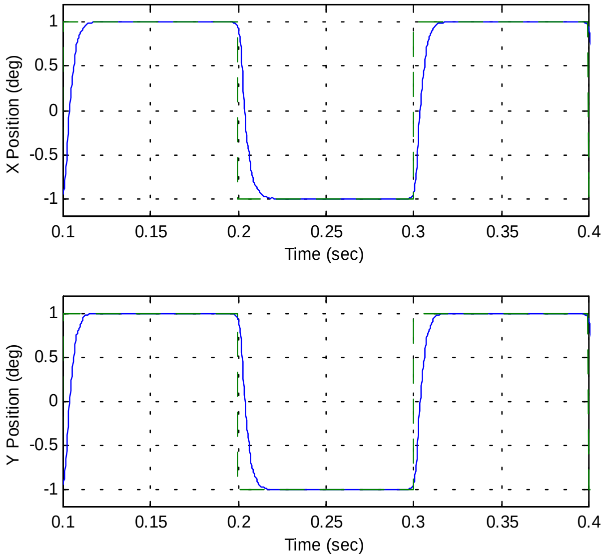


Figure 5. Step response in x-axis and y-axis for an input of +/-1 degree.

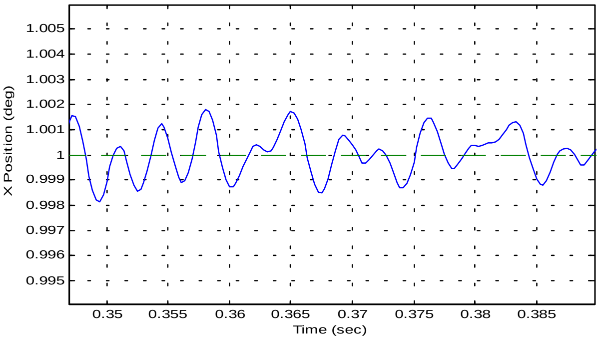


Figure 6. Close-up of steady-state position signal with noise.

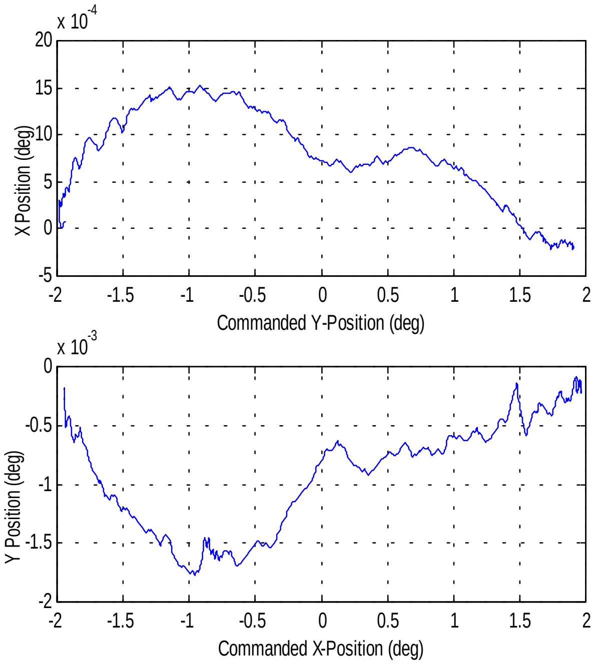


Figure 7. Mechanical coupling between the x- and y-axes.

5. CONCLUSION

The FPM demonstrates the feasibility of an efficient, low-power, large-travel pointing mechanism for intersatellite laser communication. The large travel in particular gives the device both coarse and fine pointing capability in one small package with a single control scheme, eliminating the need for separate systems.

The current test set-up shows the pointing accuracy of the FPM to be within +/-35 microradians. This value, however, is a reflection of the noise on the position signal, which is a combination of digital noise in the dSPACE system, electronic noise in the set-up wiring, and sensor noise. The first two factors can be controlled in the laboratory, and in fact would not be an issue for the flight hardware operating in space. Because there is nothing inherent in the design that causes friction or deadband, the accuracy of the FPM is defined by the accuracy of the sensors. To verify the achievement of our +/-1 microradian goal, a new test set-up with better signal-to-noise characteristics must be built.