

Development of Gimbaled Laser Beacon Mechanism

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Abstract. The Photon Satellite Project is being sponsored by the Florida Space Institute (FSI). FSI is working on the Conceptual Design Phase for this project under a contract from the Department of Defense Ballistic Missile Defense Organization. The science mission for this satellite is to characterize the atmospheric effects on a laser communications system. The development of a gimbaled laser beacon mechanism focuses on the secondary payload of that science mission, which serves as a downlink of laser signals from space to the ground station located at the Innovative Science and Technology Experimental Facility (ISTEF) at the Kennedy Space Center. This paper focuses on the development and design of a gimbaling system for a collimated laser diode beacon. The design will include selection of optics, motors, bearings, structural design, development of the equations of motion and the control design. The main objective of gimbaling the beacon is to maximize the communication time with the ground station allowing pointing capabilities to be focused and pointed at the ground station over the entire satellite pass from horizon to horizon. This will allow the laser intensity to be increased and allow visibility whether the pass is a daytime or nighttime pass.

1. Introduction:

The gimbaled beacon mechanism is one of the secondary payloads to the Photon Satellite. The gimbaled laser beacon offers many advantages over the standard omni-directional laser beacon. The collimated laser diode beacon gimbal will allow for tracking and capture of the ground station as soon as the satellite rises over the horizon. In addition, the laser light intensity can be increased over 200 times through the use of a collimated lens, allowing the gimbaled beacon to be visible even during the day passes.

This paper will focus on the selection of components for the gimbal system, the development of the equations of motion and Control design. Because the satellite is being launched via the Space Shuttle's Hitchhiker Ejection System, the NASA requirements must be adhered to as well as any restraints handed down by the FSI Photon team members. The mission lifetime for this project is one year. The satellite operates in two modes: active and passive. There are three good passes over the ground station that will be monitored and recorded per day, thus known as the active mode. Passive mode just refers to the time

when the satellite is orbiting in an area that is not passing over the ground station.

2. Mission Analysis and Design Requirements:

The mission of the Photon Satellite is determined by the payload requirements and the design constraints. Because the satellite is being deployed in the Hitchhiker Ejection System located on the space shuttle, this limits us to the orbit altitudes of the space shuttle. These orbits are located at an altitude of 352 km or 407 km, which is referred to as Low-Earth Orbit or LEO. The majority of space shuttle missions will be set aside for the construction of the International Space Station. The inclination of the 352-km orbit is 28.5 degrees, and the inclination of the 407-km orbit is 51.6 degrees.

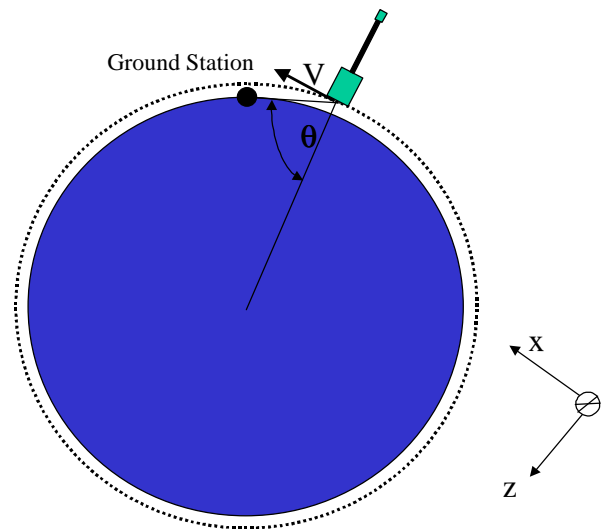
| Orbit | Columbia | Space Station |
|---------------------------|------------|---------------|
| Nominal Lifetime [days] | 162 | 474 |
| 95% Prob. Lifetime [days] | 85 | 241 |
| Passes/year | 706 | 177 |
| Nominal Passes | 313 | 230 |
| 95% Prob. Passes | 164 | 117 |

Table 2.1- Mission Orbit Summary

The Florida Space Institute is looking forward to launching the Photon satellite in the lower orbit via the Space Shuttle Columbia. According to an analysis done by FSI shown in Table 2.1, the Columbia orbit yields more probable passes because of its orbit inclination [1].

The gimbaling design requirements were dictated by team members at FSI. These requirements include that the weight of the gimbaling mechanism must not exceed 1 lbs. and the design envelope was given as 2-in. by 2-in. by 8-in. Due to restriction with the launch vehicle (Space Shuttle Hitchhiker Ejection System), the gimbaling mechanism can not protrude more than 0.4 inches from the nadir facing plate. The satellite has a lifespan of 1 year, therefore, the gimbaling mechanism will need the same lifespan. However, the gimbaling mechanism is only in operation for a maximum of three ten-minute periods per day. This gives the mechanism a duty cycle of only 2%. Power consumption is another important design parameter, and power consumption cannot exceed 1 Watt.

In order to determine the maximum pitch and roll angles of the gimbaling, the horizon angle of the satellite must be determined. This angle is based on the radius of the Earth and the altitude of the orbit. Figure 2.2 shows the scaled height of the satellite with respect to its orbit around the Earth. The angle θ , represents the maximum pitch angle that the gimbaling must be able to move in order to capture the ground station at the horizon.

Figure 2.2- Photon Satellite Orbit

Because there are two possible orbits for the satellite depending on the Space Shuttle mission at the time of launch. The maximum pitch horizon angles for each orbit are 71.4° and 70.1° respectively. This gives the full pitch angle of approximately 140° . The roll angle is dependent on the science mission. If the roll angle is greater than 45° , then the pass is not considered a good pass as far as the science mission is concerned. Therefore, the full roll angle will be 90° because the ground station can be on either side of the satellite during any science mission pass.

3. Gimbal Design:

The gimbaling mechanism will point a collimated laser beacon at the ground station as the satellite passes over it. Our challenge is to design a lightweight and reliable mechanism that will fit inside its design envelope, survive launch environments, operate in space, meet performance requirements, and withstand many cycles of operation. The gimbaling design will include selection of four main components: optics, motors, bearings, structure and control design.

3.1 Optics

The optics of the gimbaling mechanism involves the collimator, the laser diode and the connection between them. A half angle must be chosen in order to find the increase in intensity of the laser beam. The Attitude Determination and Control System of the satellite has a pointing accuracy of $\pm 5^\circ$, this will also be the pointing accuracy for the gimbaling mechanism.

Taking into account the cost, accuracy, weight and size a collimator from Wave Optics was chosen. It is 22 mm long with a 3-mm diameter. The length of the collimator is based on the focal length of the lens and its radii of curvature. The collimator uses a Gradient Index lens (GRIN) with a pitch of 0.25. Wave Optics will also connect the collimator to the laser diode with fiber optic cable.

Selection of the laser diode was based mainly on power output. Size and other parameters were also considered. The laser diode chosen from SDL Inc. is the SDL7470-P6, which has a total input power of 25 Watts. Because it will only be operation on a two-percent duty cycle, the average operating power for laser diode is 0.5 Watts per day. This amount is well within the power budget allotted to the gimbal system from the rest of the satellite.

The optic connection is extremely important to the success of the gimbal mechanism. If the collimator and the laser diode are connected directly, then the required torque for the gimbal is increased. If a fiber optic cable is used, the clearance for the fiber as well as the minimum bend radius of the fiber must be considered. The fiber optic cable must be able to bend when gimbal is turned but it can not bend too much or it will break. There are three simple equations to calculate the bend radius based on how the cable is secured. Those three types are fixed, freely flexing, and reeling duty shown in the table below.

Table 3.1- Min. Bending Radius

| | |
|------------------------|----------------|
| Fixed: | 7* cable O.D. |
| Freely Flexing: | 7* cable O.D. |
| Reeling Duty: | 14 *cable O.D. |

The reeling duty option would give a larger bend radius but it is for large spools of fiber optic cable and is not applicable to this setup. Therefore, whether the fiber is fixed or freely flexing does not affect the minimum bend radius. However, each laser diode uses a different size cable ranging from 50 m to 600 m. The SDL 7470-P6 uses the 600 m and is the optimum choice for bend radius as well. Calculating the bend radius for the 600 m cable gives a minimum bend radius of 4.2 mm.

3.2 Motors

Motor selection is a critical part in the gimbal subsystem. Selecting the proper motor is fundamental to our working mechanism. It is imperative that all motors in any space application be space rated and have some kind of redundancy for reliability, as well as simplicity.

Stepper motors are good whenever controlled movement is required. Including applications where you need to control rotation angle, speed, position and synchronism. One favorable feature of stepper motor systems is open-loop control, which avoids the complexity, stability problems, and steady-state errors associated with feedback control. Some additional stepper motor advantages include full torque at standstill, precise positioning and repeatability of movement, accuracy of 3-5% of a step, good reliability, and a wide range of rotational speeds available. There are some disadvantages when using a stepper motor. One of these is that resonance can occur if not properly controlled, and the other is that stepper motors are not easy to operate at extremely high speeds.

The most important parameters in selecting and sizing a motor are the torque requirement, resolution and speed requirement. After that there are some mechanical parameters that are important to the performance of a stepper motor system (driver and motor). These mechanical parameters of the load are either friction or inertia, or a combination of the two. Power available is another important parameter that must be considered when selecting a suitable motor.

Our calculations obtain some important properties from our gimbal mechanism, modeled in I-DEAS. All of the moments of inertia's for the outer-gimbal and the inner-gimbal are updated for the new I-DEAS model. All inertial properties and calculations were done and easily updated in MathCAD. The calculated inertial properties are as follows:

$$I(\text{outer_gimbal}) = 2.6 \times 10^{-5} \text{ kg} \cdot \text{m}^2$$

$$I(\text{inner_gimbal}) = 7.8 \times 10^{-5} \text{ kg} \cdot \text{m}^2$$

The second set of calculations involved the speed and acceleration curves of the gimbal mechanism. These calculations in the pitch axis were taken into account since this is the axis with the maximum rotating angle. This angle is 140 degrees as opposed to 90 degrees in the roll-axis. All calculations are done for the worst-case of the entire mechanism.

The velocity and acceleration curves were done using MathCAD. Only 45 degrees of the orbits original 90 degrees were analyzed in order to simplify the mathematics, assuming symmetry. The change in the angle of the gimbal with respect to the ground station was then plotted against a known time interval, as shown in Figure 3.2 on following page.

The time interval is 45 seconds over 45 degrees, and so the time step is one second. The velocity curve is the change in angle (degrees) plotted against the time interval of one-second. The maximum velocity is 1.27 degrees/ second. The plot of the acceleration curve is the change in velocity with respect to the one-second-time interval. Our maximum acceleration is 0.017-degrees/ second², shown in Figure 3.3 on following page.

Figure 3.2- Velocity Curve

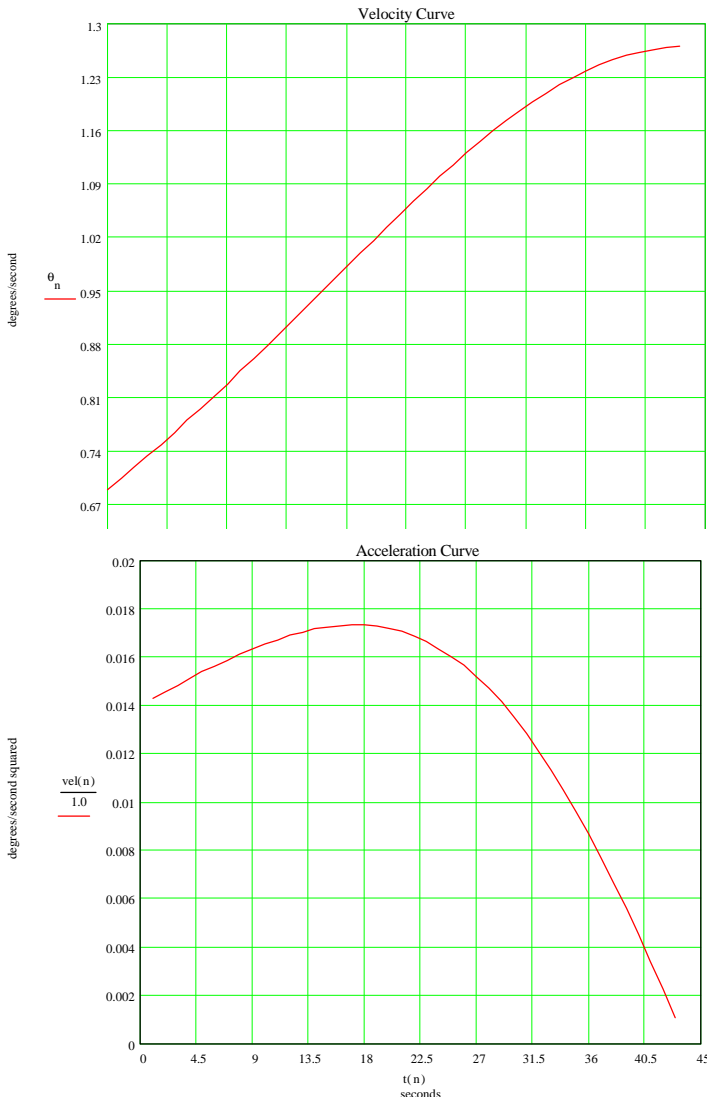


Figure 3.3- Acceleration Curve

The maximum Torque is now calculated by using the maximum acceleration multiplied by the maximum inertial property, which is that of the outer-gimbal.

The absolute maximum Torque experienced by the gimbale mechanism will be in the order of 0.008 mN*m (milli-Newton meters). This torque includes a very large safety factor and still proves to be quite nominal.

Once the maximum torque was calculated and proved almost negligible, the major concern was the size of the stepper motor. Due to limited space provided for this secondary payload, the motor length has to be less than or approximately 0.6 inches. A manufacturer of small stepper motors was found called Phytron Incorporated, located in Massachusetts. They manufacture extreme environment stepping motors, and guarantee the smallest commercially available stepper motors with the largest step angle.

The motor chosen was the VSS 25.500.0.6. It is a two-phase hybrid stepping motor with 500 steps/revolution. These 500 steps/revolution are equal to 0.72 degrees/step. The diameter of this motor is 25mm or 1 inch, and the length is originally 31mm, which is too long for our gimbal mechanism. However, Phytron will customize the motors to our design needs and it will be 0.6 mm in length. There is a reduction in torque, but the holding torque on the VSS 25 is 12 mN*m, which well exceeds our required torque and therefore we can afford the decrease in torque. This motor has a step accuracy of 5% and weighs only 0.2 lb. Because the step angle is very good for this small a motor, a gearhead reduction will not be used. A gear would only increase the length of the overall motor, which is not possible, and would increase the torque, which is not needed. Phytron has a long and successful flight history of their stepper motors.

3.3 Bearings

Bearing selection is dependent on two main factors: motor torque and speed requirements. The bearings are not being designed, rather bought off the shelf or customized from a company. Requirements

such as the life cycle and radial or axial loading must be determined. These factors drive the selection and optimization of the bearing type and size. Standard criterion for bearing options include: static and dynamic loading and contact stresses, whether the motion is continuous or reciprocating, rotational speeds which are dictated by the motor, life cycles, and part tolerances. Several factors must be considered when selecting precision instrument bearings for space applications. Space bearings require an additional level of criterion which include vacuum compatibility, lubrication options, launch vibration levels, and temperature gradients that are experienced by the mechanism from launch to insertion and the throughout mission operation lifetime. Modifications to the structure and final motor selection and speed requirements as well as final bearing configuration will be discussed.

Ball bearings are used in space mechanisms more than any other type of bearing because of their running precision, good load capacity, ease of lubrication, low friction and availability in an enormous range of sizes and cross-sections. Therefore, the Conrad or Deep Groove Ball Bearing proves to be the desired bearing type for this space application.

The selection of lubrication in space or vacuum applications is driven primarily by the outgassing qualities. Because the payload involves optics, outgassing of the lubricant would probably cause debris to contaminate the lens and therefore destroy the laser light being transmitted to the ground station. Since, this science mission is to characterize the effects of the atmosphere on laser transmissions, any contamination due to outgassing is unacceptable. Solid lubricants generally possess the ability to operate in extreme temperature environments with little or no contamination of surrounding critical surfaces [2]. Since this is a major concern with the majority of liquid lubricants this leaves solid lubrication as the only viable option. The most widely used solid lubricants on spacecraft consist of films derived from and Molybdenum Disulfide, MoS₂.

The bearing selection requirements were dictated by the motor selection and mass moment of inertia properties of the gimbal. The gimbal will have movement in both the pitch and roll axes, so all radial and axial loads are important in the selection process. The motors selected are identical for both the pitch and roll movement, this simplifies the bearing

selection and makes the only difference between bearings dependant on the assembly process. Based upon the maximum torque calculations the maximum radial load and axial load were calculated to be $F_r \cong 2.74 \times 10^{-6}$ lbs and $F_a \cong 4.27 \times 10^{-7}$ lbs, respectively. These calculated loads are negligible and any bearing currently available will achieve this.

There are a total of three bearings that are needed for the gimbal design. Two bearings are needed for the movement of the inner gimbal assembly, and one bearing is needed for the outer gimbal assembly. The Miniature Precision Bearing, The MPB division of Timken provides Space Qualified Bearings that meet the needs of the Gimbaled Beacon. The bearings for both the outer and inner gimbal assemblies are shielded deep groove ball bearings, to prevent any contamination to the optics, with MoS₂ dry lubricant. The only difference between the inner bearings and outer bearing is that the outer bearing has a flange for assembly purposes. The part numbers given by MPB are S614FCHHE7P25 and S614CHHE7P25L.

3.4 Structure

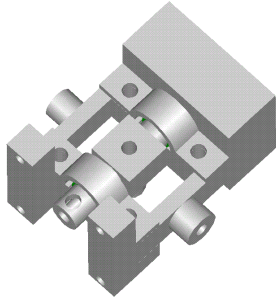
Material selection in the case of the gimbal design was very important. The material selected had to be lightweight yet able to withstand the extreme environment of space. The list of possible materials that can be used in the gimbal is short. Among the choices are aluminum, steel, and composites. The chosen material had to have a small coefficient of thermal expansion in order to minimize the effects of the thermal gradient. Taking all these factors into consideration, Aluminum turned out to be the best choice. Aluminum 6061-T6 was chosen because of its proven track record in space applications.

The design of the gimbal had to be optimized for area. It had to be designed as small as possible since there is only a limited space available to mount the gimbal assembly. An initial design parameter of a volume of 2-in. by 2-in. by 8-in was given. Additional space can be created in the event that the gimbal exceeds the intended size.

The gimbal consists of two sections, an inner assembly and an outer assembly. The inner assembly rotates in the pitch axis from -45° to 45° . The outer gimbal rotates in the roll axis to give the gimbal a pointing ability of 140° . The inner gimbal housing contains a chuck as well as the collar to use to hold the laser collimator in place. It also contains the hole for the shaft as well as a hole for the setscrew. The

outer gimbal is a rectangular shape and encloses the inner gimbal, as shown in Figure 3.4.

Figure 3.4- Gimbal Structure

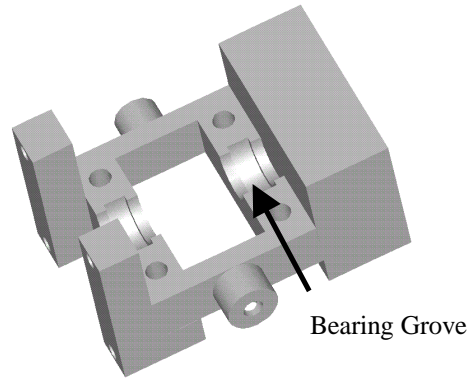


The outer gimbal is also used to house the two bearings needed to provide the inner gimbal with free movement. Two clamps perform the double duty of holding the bearings in place as well as providing structural support to the outer gimbal. The outer gimbal also consists of a counter weight to compensate for the weight of the inner roll motor.

The gimbal profile chosen was rectangular in shape in order to keep machining difficulty at a minimum. This shape made it easier to mount the motors and bearings as well as assemble the entire gimbal together.

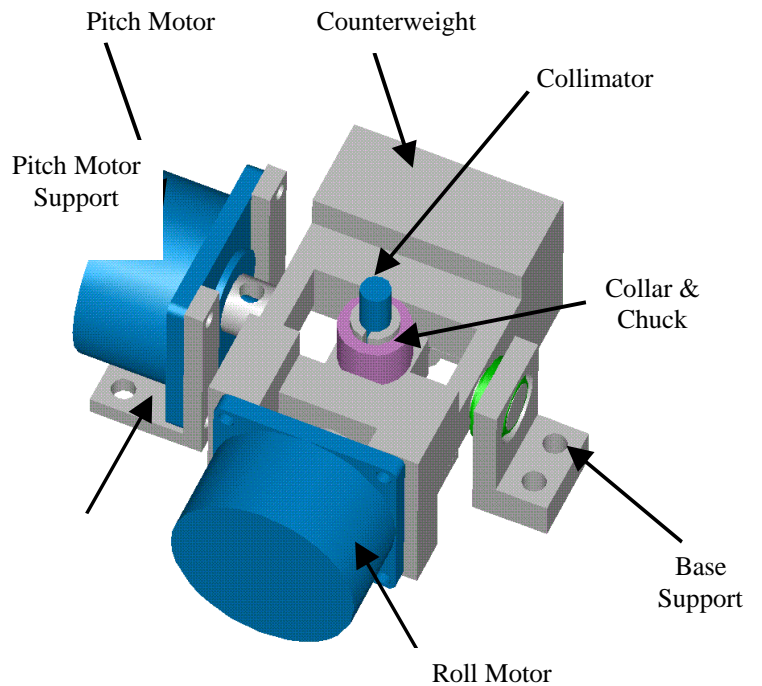
The inner gimbal is a single piece made from a machined block of aluminum. The chuck is integrated into the inner gimbal design to reduce its size and complexity. Assembly of the entire gimbal had to be considered since the inner gimbal is one piece. A method of mounting the inner gimbal to the outer had to be designed. The bearings used have to be held in place along with the shafts of the inner gimbal. Groves were machined into the outer gimbal to hold the bearing in place and prevent it from moving in the axial direction (Figure 3.5). Clamps are then bolted onto the outer gimbal, holding the bearings and shafts in place.

Figure 3.5- Bearing Placement



The motor mounts for the roll motor as well as the counter weight was integrated into the design of the outer gimbal. This one-piece design reduced individual part numbers as well as adding strength to the overall design, as shown in Figure 3.6.

Figure 3.6- Gimbal Assembly



The collimator is attached to the inner gimbal by a collimator chuck and collar. The collimator chuck

prevents the collimator from moving axially throughout operation and the launch environment. The gimbal mechanism is integrated to the spacecraft by directly attaching the base supports to the nadir plate.

3.5 Power:

There are three sources of power for the gimbale beacon: The laser diode and the inner motor and outer motor. The allotted average power for the gimbal design is 1 W on a 2% duty cycle. In order to calculate this value, the independent power requirement for each unit must be specified.

The laser collimator operates with a forward voltage, which is dependent on the operational current times the resistance plus a voltage factor, resulting in a forward voltage of, $V_f = 1.92$ V, and a total Power of 23.04 W.

The motors for the inner and outer movement are the same, therefore they contribute the same amount of power. The operating amperage is 0.6 amps, with an operating voltage of 13 ohms. This results in a total operating power of 4.68 W for each motor.

The total power budget for the gimbale beacon is shown in Figure 3.6. This shows that the gimbal design is well under the 1 W of average power on a 2% duty cycle.

Figure 3.6 Operational Power Budget

| | | |
|------------------------------|---|-------------------------------|
| • Laser Diode | ⇒ | 23.04 W |
| • Inner Gimbal Motor | ⇒ | 4.68 W |
| • Outer Gimbal Motor | ⇒ | 4.68 W |
| <hr/> | | |
| Total Operating Power | ⇒ | 32.4 W |
| | ⇒ | 0.65 W (2% duty cycle) |

4.0 The Equations of motion:

The equation of motion for the gimbale mechanism have been developed. This system has two degrees of freedom of motion in roll and pitch axis. Hence the motion equations are given by(both are not coupled):

$$t_q = I_{xx} \ddot{f} + m_f g l_f \sin f + k_f l_f^2 \dot{q}$$

$$t_f = I_{yy} \ddot{q} + m_q g l_q \sin q + k_q l_q^2 \dot{q}$$

Where:

- q & f : Roll and pitch angles, respectively.
- t_q & t_f : Control torque applied to the respective axis of the mechanism.
- k_ϕ and k_θ : Friction Factor.
- m_ϕ & m_θ : Mass of each axis.
- l_ϕ & l_θ : Lengths from the center of mass to the axis of rotation of the mechanism in roll and pitch axes respectively.

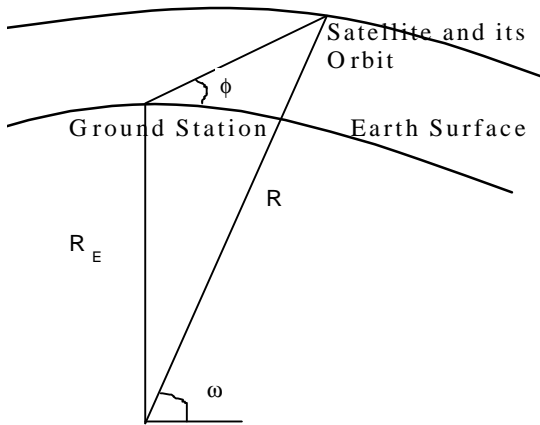
The motion of the satellite is considered to be in the equatorial plane for both roll and pitch axis. Using this equation we calculate the desired trajectory for the position of the gimbale mechanism in both pitch and roll axes. It follows from the sine rule that:

$$\frac{R}{\cos j} = \frac{R_E}{\sin(w-j)}$$

Then, the desired trajectories for the gimbale mechanism on each axis are obtained by differentiating the above equation as

$$j \dot{} = \frac{\dot{w} \cos(w-j)}{\cos(w-j) - \left(\frac{R}{R_E}\right) \sin j}$$

Fig4.1: Motion of the satellite in Equatorial Plane.



5.0 Control Design:

The Control is designed for the trajectory for tracking of the system. The proposed controller is in form:

$$t_q = K_{d1} \dot{q} + K_{p1} q + mgl_q \sin q$$

$$t_f = K_{d2} \dot{f} + K_{p2} f + mgl \sin lf$$

Where:

K_d and K_p are the constants for derivative and proportional part of the controller.

For the simulation, the friction factor was neglected.

The values of the parameters for both roll and pitch axis are:

| | |
|---------------------------------|-----------------------------------|
| <i>Roll Axis:</i> | <i>Pitch Axis:</i> |
| $I_{xx}=263.19 \text{ gm cm}^2$ | $I_{yy}=786.1086 \text{ gm cm}^2$ |
| $K_p=178$ | $K_p=196.156$ |
| $K_d=22.69$ | $K_d=23.8$ |
| $W_n=13.34$ | $W_n=14$ |
| $\xi=0.85$ | $\xi=0.85$ |
| $T_s=0.3525$ | $T_s=0.336$ |
| $\Delta T=1.7625$ | $\Delta T=1.68$ |

Note that ΔT is the minimum time interval for the motor to move in each step of for each axis of rotation denoted as the minimum resolution. It is varying at each point on the when θ and ϕ curve. Here ΔT indicates the minimum value of time which is critical and occurs when θ and ϕ approaches '0'. If T_s is the settling time, then by the rule of thumb, it can be expressed as: $T_s = \Delta T/5$.

The actual trajectories of θ and ϕ are obtained. These are then compared with the desired trajectories of θ and ϕ . The initial conditions for the simulation are set to be:

$$q(0) = f(0) = 0$$

$$\dot{q}(0) = \dot{f}(0) = 0$$

The roll and pitch axes are plotted in degrees considering the position of the satellite exactly above the ground station as zero. The maximum operation ranges for pitch and roll are 140 and 90 degrees respectively.

The Simulation results are shown in Figure 5.1 and Figure 5.2, and they show that the gimbaled mechanism is controlled with the minimum errors. The improvement factor for the Gimbaled mechanism is 260.

Figure 5.1. Comparison of actual trajectory and desired trajectory for the roll axis.

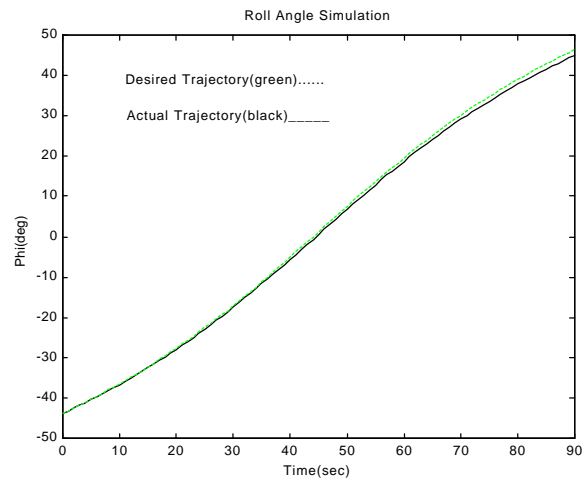
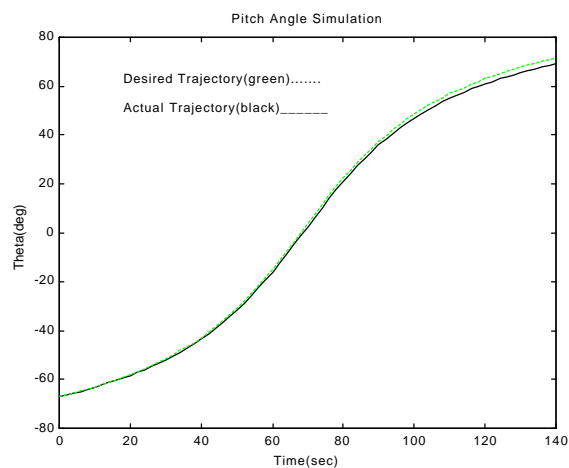


Fig.5.2 Comparison of actual trajectory and desired trajectory for the pitch axis.



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6.0 Conclusion:

The Gimbal Mechanism designed for the Photon Satellite in a circular orbit guarantees desired performance with the rigidity, which is verified through simulation. This mechanism can be used for various pointing and mapping devices used for Satellites in similar applications.

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