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A Multi Stage Pointing Acquisition and Tracking (PAT) Control System Approach For Air to Air Laser Communications

Mike Borrello
Trex Enterprises, San Diego, CA
stablesystems@ieee.org

1.0 Introduction

Nearly half a century has passed since the laser was modulated, providing for the first time a means to send high speed information at distance over a beam of light. Simple in concept, this method of communication can provide data rates that far exceed communications by radio waves, however requiring an extremely accurate and stable line of sight (LOS) between the transmitting laser and light detector. Today engineers are faced with a much greater challenge as they seek to apply laser communications over hundreds of kilometers in the open atmosphere aboard aircraft in flight. Disturbing vibrations on the aircraft together with atmospheric scintillation introduces pointing and tracking errors in the LOS that can either degrade or entirely prohibit the ability to communicate by laser. This is where communications turns to control engineering for solutions. For relatively low power lasers with small divergence, mechanisms and their controls must be capable of pointing, and then tracking within a few microradians over a field of regard (FOR) that exceeds a full hemisphere. This presents a formidable problem for this disturbance environment.

One approach is to use a system of multi nested gimbals that point the lasers and sensors aided by an inertial navigation system. A multi staged approach, as opposed to a single stage system, applies control to two or more stages that each handles different dynamic ranges. Although this introduces greater complexity, it can significantly reduce costs on sensors and actuators that, in the single stage system, would require extremely high dynamic range. This paper discusses a multi staged gimbal system used on the Recce Intel Laser Crosslink (RILC) system developed for research by Trex Enterprises. Although a complete description of the RILC system has been published [1], [2], that describe the optical and communications components, this paper focuses, in greater detail, on the control systems for RILC. An overview of the RILC system is provided and controls for each subsystem are described. Finally, results of pointing and tracking from actual field testing over a 50 km test range are presented.

2.0 System Overview

The RILC control system has one ultimate goal; to establish and maintain a stable, bidirectional laser communications crosslink between two aircraft in flight. This goal can further be broken down into 2 basic requirements which apply to each communications terminal:

(1) Maintain accurate and stable position of the received communications laser image, and
(2) Provide accurate and stable pointing of the transmit laser.

To reach a state of stable communications, each system must first acquire the other within its coarse track sensor field of view. This means that each system must initially point towards one another with precision that results in mutual illumination within the divergence angle of the wide field of view (WFOV) beacon laser. For pointing the receiver, the system uses dual nested 2 axis gimbals that rotate the WFOV and narrow field of view (NFOV) laser beacons and sensor boresights with respect to the aircraft frame. Inertial navigation aids, located on the base of each terminal, measure terminal position, velocity and attitude in an earth centered, earth fixed (ECEF) reference frame. This information is mutually shared between the two terminals via radio transmissions to determine body frame pointing commands, derived from ECEF, for each terminal. Resolvers on each gimbal axis measure angles relative to the aircraft base. Together the navigation aids and resolvers help controls to position the sensor and laser boresights with the true LOS connecting the two aircraft in an inertial frame. Figure 1 illustrates, by a one dimensional diagram, how the various angles of the multi staged gimbal relate to one another.

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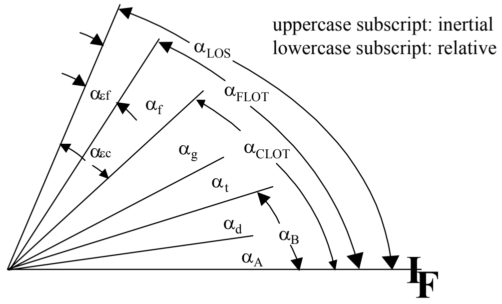

Figure 1 Angle Reference System

α_{CLOT}	Coarse camera and receive detector boresight
α_{FLOT}	Comm laser pointing angle
α_{LOS}	True Line of sight
α_f	Fast steering mirror angle
α_g	Gimbal angle
α_t	Turret angle
α_d	Aircraft disturbance
α_A	Aircraft attitude
α_B	Base angle (attitude plus disturbance)
$\alpha_{\varepsilon c}$	Coarse track error
$\alpha_{\varepsilon f}$	Fine track error

Perfect alignment between the host and target terminals requires that $\alpha_{CLOT} = \alpha_{FLOT} = \alpha_{LOS}$. This means that α_g and α_t must be controlled as α_B changes. This requires measurement of α_g, α_t, α_B, $\alpha_{\varepsilon c}$ and $\alpha_{\varepsilon f}$.

The outermost AZ-EL gimbal is a turret which provides low speed, stiff positioning of α_t over a wide FOR. Nested within the turret is another EL-AZ gimbal which has faster positioning capability of α_g over a smaller FOR. Cooperative pointing between the two gimbal systems is accomplished by slaving turret angle relative to the gimbal during pointing to acquire the WFOV beacon in the coarse camera FOV. The turret is actuated by a geared permanent magnet synchronous (PMS) motor. Gearing introduces positioning errors from backlash and hysteresis, but the inner gimbal axes, actuated by direct drive DC motors, are able to correct for this error. During pointing for acquisition, the gimbal loops are referenced to the total angle measured in the body frame (turret plus inner gimbal). The turret is commanded to position itself to keep the gimbal centered within its smaller FOR within a small deadband. This provides full, accurate positioning of the camera boresight and beacon lasers and accommodates continuous aircraft linear and angular motions until track is engaged. Cooperative pointing provides pointing accuracy of the gimbal over the hemispherical FOR offered by the turret.

Acquisition of the WFOV beacon occurs when pointing causes the image of this beacon to appear on the coarse beacon camera. Once detected, the system captures the beacon image in the coarse camera 20 mrad FOV. Image position on the camera is controlled to a calibrated boresight position for the avalanche photodiode (APD) detector boresight near coarse camera center. This is done by closing a feedback positioning loop between the gimbal and coarse camera image centroid calculations. For coarse track, slaving of the turret to the gimbal resumes to maintain the gimbal near the center of its stroke as the aircraft move relative to one another, and as the host aircraft attitude varies. Centering by the turret provides maximum swing for the faster gimbal track, designed to attenuate angular disturbance to fewer than 100 μradians rms.

With coarse track engaged, the APD receiver, calibrated to the coarse track camera boresight, receives light from the communications lasers. At this stage, requirement (1) is met.

Each inner gimbal is bore sighted with, and points both the WFOV and NFOV beacons. The pointing of the transmit communications lasers, which are also bore sighted with these beacons, is further adjustable using a fast steering mirror (FSM) with basis in the inner gimbal reference frame.

Stable coarse track results in the NFOV beacon from the target terminal to appear in the 640 μradian FOV of the host fine camera. A feedback control loop for NFOV beacon tracking then centers this beacon image on the fine camera by positioning the FSM which changes the position of the NFOV beacon image on the fine camera. This stabilizes the FSM reflective surface over a high bandwidth referenced to the true LOS within 7 μradians rms, allowing the communications laser, with a very narrow divergence angle, to illuminate its target. This meets requirement (2), and the goal is completed; a stable bidirectional communications link is established.

3.0 Gimbal Controls

Gimbal controls provide multiple purposes in the multistage pointing acquisition and tracking (PAT) system, but the primary purpose is to reject mid range disturbance during point and track out to about 30Hz. Gimbal controls use a simple PI controller referenced to a position sensor. An inner rate loop, using a two axis dynamically tuned (DTG) gyro, provides gimbal damping against a ceramic bearing suspension and attenuates inertial based rate disturbances. The challenge in the gimbal control is transitioning from resolver based feedback during pointing to the coarse camera during tracking. These feedback sensors are each based in a different reference frame which requires switching of the input command coincident with feedback switching. This provides a bumpless transfer of control. Detection (or loss) of the WFOV beacon image in the coarse camera FOV is used to initiate a transition between pointing and tracking modes, and exponential trajectories are generated based on start and end point positions for each mode. The resolver has a resolution of 24 μradians, and coarse detector centroid estimates are somewhere near 8 μradians. For tracking, region of interest (ROI) switching of the coarse camera occurs once the image is captured and moved to center, decreasing the FOV to 9 milliradians but increasing frame rates from 110 to 250/second resulting in an increase in closed loop bandwidth from 12 Hz to about 30 Hz.

4.0 Turret Controls

The purpose of the turret controls are to provide pointing and centering of the inner stage gimbal axes. The high gear ratio between the PMS motor and turret mechanical load provides high torque stiffness. This is necessary to help resist friction caused by environmental seals and aerodynamic torques induced in flight. Inner current and velocity loops are used for motor control, and an outer proportional loop is closed on resolver position measurements which also have a 24 μradians resolution. For the turret, pointing knowledge is more important than pointing accuracy. Any residual error in the turret is compensated for by the gimbal, which for the pointing loop is referenced to total body angle. Gain in the position loop is adjusted to provide a small displacement bandwidth near 10 Hz. Turret position commands are generated based on initial and final positions and constant acceleration profiles that limit acceleration and velocity.

5.0 FSM Controls

The purpose of the FSM controls is to further isolate high band disturbances for stable pointing of the communication lasers. Since the FSM is located on the inner (AZ) axis of the gimbal, it can be considered as a third stage of the multi stage system. Disturbances for the FSM include both residual vibrations from the gimbal and atmospheric scintillation that perturbs NFOV beacon centroid measurements from the fine camera. The FSM is actuated by a triad of piezoelectric actuators that, by appropriate transform, provide independent control in two axes. Since the FSM is very high bandwidth, simple integral compensation can be used with feedback from the fine camera centroid calculations. Figure 2 shows the closed loop system where optical elements including a telescope, focusing lens and the mirror itself determine open loop gain.

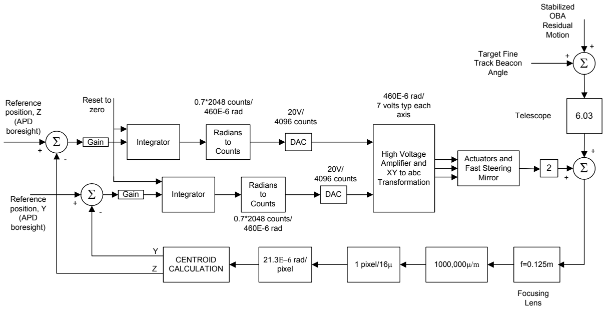

Figure 2 FSM Track Loop

Loop gain is adjusted to roll off higher frequency resonance in the FSM assembly at about 2500 Hz. The closed loop bandwidth is adjusted to about 300 Hz as shown in figure 3, the measured frequency response for one axis of the fine track closed loop system.

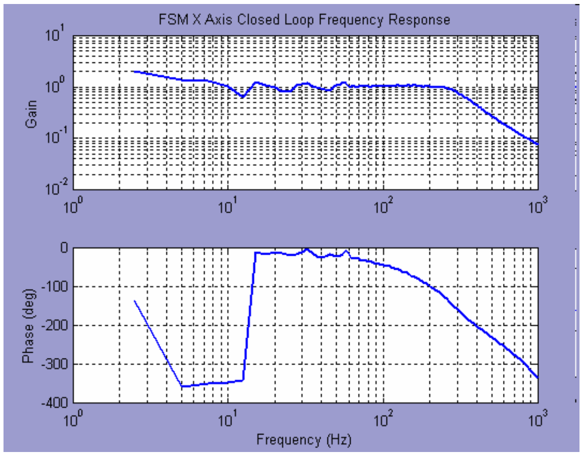

Figure 3 FSM Closed Loop Frequency Response

6.0 The Integrated Control System

For acquisition, total body angles (turret plus gimbal) are compared with the estimated LOS rotated into the body reference frame. This estimate is determined by a navigation algorithm that uses integrated Global Positioning System and inertial navigation system (GPS/INS) measurements based in each terminal. For flight operation, a Kalman filter is used to propagate this reference for initial acquisition and in the background as a 'safety net' should intermittent loss of centroids occur.

Although the individual control loops are in principle simple structures, interaction and coordination of the controls became a significantly complex structure requiring synchronization, transition controls and safety measures to prevent damaging a delicate and expensive optics bench. To speed the process from simulation concept to a real time working system, the real time data acquisition and control capabilities of VisSim™ were utilized to realize a processing engine that provides the bulk of control operations. This process, except for some work writing dynamic link libraries (DLL's), eliminates having to specify, write and validate software code by using a one step process from simulation to hardware in the loop simulation (HILS). Running on a PC, and directly interfacing to sensors, actuators and companion GUI & DSP processors in a VME chassis, VisSim™ provides all the controls that run at a sample rate of 10 kHz or less. Processes requiring faster computation rates, such as coarse and fine camera centroiding, and the fine beacon control loop, are calculated using a DSP. Processed information and interactive control from these DSP-based control loops are interfaced and coordinated with the PC by means of analog and digital serial interfaces. The navigation system, an H764-G from Honeywell was interfaced directly to VisSim™ using a PCI/1553 interface board from Excalibur Systems and a custom DLL.

A hardware in the loop simulation (HILS), initially built for development, evolved into a turn-key processing engine for each laser communications terminal that interfaces with the VME-based computer for flight operation.

7.0 Test Results

A pair of RILC terminals was installed on the laser test range at White Sands Missile Range (WSMR), New Mexico between North Oscura Peak (NOP), elevation 7900 ft. and Salinas Peak, elevation 8985 ft. to test PAT and communications capabilities. The terminal at NOP was mounted atop a hydraulic (Stewart) platform providing simulated 3 DOF aircraft motion. Figure 4 shows the RILC terminal at NOP mounted on the Stewart platform.

Figure 4 RILC Terminal at WSMR, NOP

To evaluate operation under flight conditions for mountaintop tests, simulated aircraft motion and vibrations were used to command the Stewart motion platform. The platform is interfaced with a control computer also running VisSim™ which synthesizes motion based on dynamic models of aircraft and atmospheric turbulence. Figure 5 displays the power spectral density for the yaw axis motion simulated on the platform, measured by ATA's MHD rate sensors sampled at 1 KHz. This disturbance level is conservative in that it exceeds power at all frequencies compared to a PSD derived from measurements taken on an actual KC-135 aircraft.

The requirement to slew and engage track is 10 seconds. Figure 6 shows the results of a test that verifies this requirement where the turret slews about 70 degrees in AZ and 50 degrees in elevation as indicated in the lower plot of the figure. The upper part marks first the start of acquisition, and secondly the engagement of track and switching to sub frame tracking. This shows an acquisition time of less than 5 seconds for this particular slew angle.

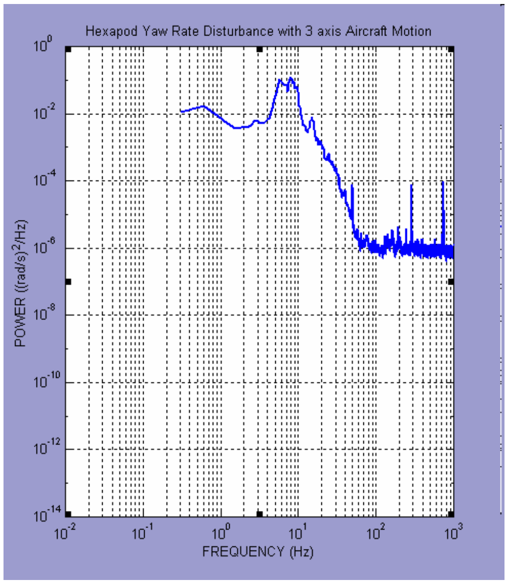

Figure 5 PSD, Aircraft Yaw on Stewart Platform

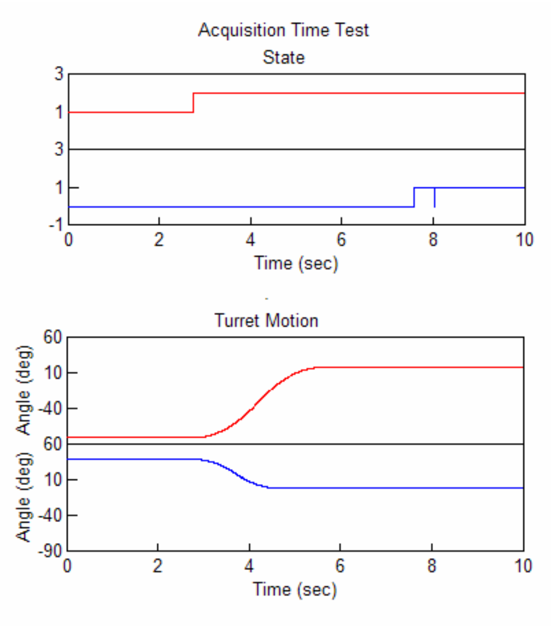

Figure 6 Acquisition Test Results

Figure 7 shows a plot of coarse camera centroids with aircraft motion disturbances. The centroid plot illustrates, spatially, the residual motion of tracking controls.

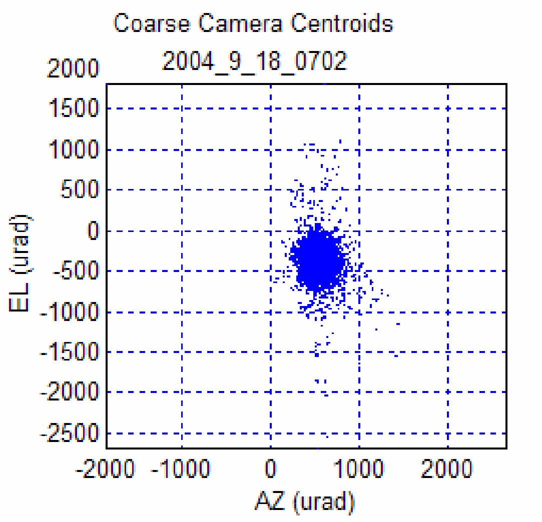

Figure 7 Coarse Track Centroids

8.0 Conclusions

Although other approaches to free space laser communications have been proposed, the requirement to point over a large FOR while accommodating vibrational disturbances on moving platforms, also constrained by relatively eye safe lasers, reinforces a gimbal based solution. This is the approach adopted by RILC which, in field testing at WSMR, has demonstrated feasibility of multi staged PAT controls for air to air applications, but has also revealed critical issues in the system design that limits the ability to establish and maintain communications unrelated to the PAT controls. These issues were specifically an insufficient dynamic range of the camera sensors used in the coarse and fine track loops.

Both the coarse and fine cameras used on RILC use an older charge coupled device (CCD) technology with a high fill factor and thus are prone to blooming. Blooming is caused when excess charge in light saturated pixels spill over into other surrounding pixels causing the beacon image to become distorted in shape. Intensity gradients are clipped at maximum during blooming causing centroid calculations to become biased and noisy as subpixel resolution is essentially lost. Liquid crystal variable retarders (LCVR's) in the coarse and fine optics can attenuate some of this light to avoid blooming, but this further reduces the cameras 12 dB dynamic range critically needed to also sense low intensity light during fades caused by scintillation. The limitations of a camera with 12 dB dynamic range in an estimated scintillation environment of 20 dB results in feedback sensors that essentially 'open the loop' on a regular basis during tracking.

The controls design does accommodate occasional dropout by the coarse camera by reverting to pointing and acquisition controls which reference the EGI and resolvers until the beacon can be reacquired, but dropouts were found to be so frequent that communications could not be established. This is because pointing of the communications depends on continuous and stable fine track with the FSM which in turn depends on continuous and stable tracking of the coarse beacon image in the gimbal loop.

For the fine track loop, when the environment did allow coarse tracking, residual vibration in the gimbal track loop, together with scintillation disturbance on the NFOV beacon image caused the FSM to operate at full stroke in X and Y axes. Saturation in the stroke of the mirror resulted in loss of centering the NFOV beacon image, and inability to provide stable pointing of the communications laser. Part of the problem here is that the coarse track rates for subframe sampling were reduced from the 250Hz base to 76 Hz in an attempt to increase integration time in the camera to increase image integrity. This however required reducing gimbal loop bandwidth to maintain stability which increases disturbance residual on the gimbal. The residual in turn spills into the fine track loop. Even if full frame rate is used it is estimated that FSM stroke will still be considerably consumed by scintillation disturbance which may have been underestimated. Increasing FSM stroke is recommended

Pointing controls also revealed another but less serious issue in the multi stage approach. Backlash in the turret gearing was found to cause low frequency limit cycle oscillations that occurred on occasion at specific but undeterminable operating points. Control solutions were sought in the turret loop in an attempt to overcome the limit cycles including deadband and deadband with hysteresis on servo error, but drift in the motor velocity loop prevented the use of either of these methods. Rate feedback in the proportional loop was found to eliminate the limit cycles however slowing turret speed such that slew requirements cannot be met. The best solution for this problem turns out to be mechanical design change that would add preload torque to the turret gearing system to take up backlash. Another option is to eliminate gearing entirely and replace the turret drive with direct drive DC torquers.

9.0 References

[1] Feldman, R.J., Gill R. A. “Development of a laser crosslink for airborne operations”, Proceedings *IEEE Military Communications Conference (MILCOM 98)*, Boston, MA, October 18-21 1998.

[2] Arnold R.L., Woodbridge E.L., Smith G., Taylor G.L., Trissel R.G., Feldmann R.J,Gill R.A. **, “**500-km 1-GBPS airborne laser link”, *Proc. SPIE, Free-Space Laser Communication Technologies* X; G. Stephen Mecherle; Ed. Vol. 3266, p. 178-197, May 1998

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