

## UID-based control loop for precision beam pointing

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### ABSTRACT

A pointing control system has been designed based on a CCD array and a fine steering mirror. The control system accurately points a transmit laser ahead of an incoming beacon laser without requiring accurate pre-stabilization of the beacon line of sight. The digital design of the control loop and a laboratory demonstration of CCD-based laser pointing are presented.

### 1. INTRODUCTION

A technique based on a high frame rate CCD array has been developed to perform spatial acquisition, high bandwidth tracking, and precision beam pointing for spacecraft laser communications. This technique<sup>1-3</sup> uses a single detector array and a single steering mirror, and does not require additional sensors and fine steering elements for spatial acquisition and point-ahead compensation. Acquisition of an incoming beacon laser on the CCD array is performed first by searching in the spacecraft attitude uncertainty zone. The beacon line of sight is then coarsely stabilized on the CCD array in a telescope gimbal control loop. To measure the instantaneous point-ahead angle, a portion of the outgoing transmit laser is imaged onto the CCD array where the spatial separation between the beacon and transmit spots represents the point-ahead angle. The measured point-ahead angle is compared with a point-ahead angle calculated based on relative velocity between spacecraft and beacon. The point-ahead error is then processed by a digital signal processor to generate a control signal to drive the steering mirror. The steering mirror control loop operates independently of the gimbal control loop and accurately stabilizes the point-ahead angle. This technique provides closed loop control of the point-ahead angle, eliminating the need for accurate stabilization of beacon line of sight and open loop pointing of the transmit laser. This paper describes the design and a laboratory demonstration of the CCD-based steering mirror pointing control loop.

### 2. CONTROL LOOP DESIGN

The block diagram of the pointing control loop is shown in figure 1. The input to the control loop is a known point-ahead angle that is calculated based on the relative velocity between the spacecraft and the beacon laser. The output of the control loop is the actual point-ahead angle, and is measured by finding the centroids of the transmit and receive laser spots on the CCD array and performing the subtraction. A CCD array size of 100x100 is needed to achieve a centroiding accuracy of better than 1  $\mu$ rad in a field of view of 1 mrad. To provide compensation in the control loop, a digital filter is implemented in a digital signal processor (DSP) and applied to the steering mirror through a pair of 16-bit digital to analog converters. Figure 2 is the timing diagram of the control loop, and shows time delays associated with CCD integration, CCD frame transfer, CCD readout, centroid and filter computation, and zero order hold due to digital to analog converters. The digital filter is designed to provide compensation for the steering mirror resonance and for the control loop time delays. After design of the filter, a simulation with the block diagram model in figure 1 is carried out to compare to analytical prediction of the control loop performance.

A direct digital design<sup>5</sup> of compensation was carried out in the z-domain by writing the compensation transfer function as,

$$H_c(z) = \frac{1}{H_m(z)} \frac{H_d(z)}{1 - H_{cl}(z)} \quad (1)$$

where  $H_c(z)$  is transfer function of compensation,  $H_m(z)$  is the cascaded transfer function of steering mirror and all the loop delays including zero order hold, and  $H_d(z)$  is the transfer function of the desired closed loop response. This method allows direct selection of closed loop poles based on the desired closed loop bandwidth and stability margins, and subsequent derivation of the compensation transfer function needed to achieve the desired closed loop performance. The transfer function of the control loop disturbance rejection is given by,

$$H_{dr}(z) = \frac{1}{1 + H_c(z)H_m(z)} \quad (2)$$

which is used to predict residual rms pointing error due to spacecraft platform jitter. A type 1 compensation filter was designed using this method for the CCD-based control loop for a sampling rate of 2KHz. This compensation will result in stable operation and  $< 1.5 \mu\text{rad}$  residual rms platform jitter assuming a typical spacecraft jitter environment similar to that of the Landsat spacecraft<sup>6,7</sup>. The performance predictions of the control loop with this design were verified by carrying out a block diagram simulation.

#### 4. DEMONSTRATION OF CCD-BASED POINTING

Figure 3 shows a simplified block diagram of the laboratory setup used in the demonstration of CCD-based pointing control loop. The CCD camera hardware with interface to a digital signal processor (DSP) has been designed and built as described in reference [4]. A HeNe laser was used as the beacon and was imaged on the CCD camera after passing through a pair of one-dimensional steering mirrors to simulate platform jitter. A second HeNe laser was used as the transmit laser and was pointed by a General Scanning TABS II mirror and imaged on the CCD array. The transmit and laser spots each comprised about  $2 \times 2$  pixels on the CCD array. The DSP processor was used to command the vertical and horizontal shifts in the CCD array, receive CCD pixel data in two  $6 \times 6$  windows of interest around the transmit and beacon laser spots, perform centroiding on the pixel data, compute the mirror control signal, and drive the steering mirror. A pair of 16-bit digital to analog converters with a voltage range of  $\pm 5$  volts were used to provide the mirror control signal.

The focus of the demonstration was to close the control loop by using optical feedback from the point-ahead angle. Therefore, the telescope gimbal control system, which will coarsely stabilize the receive line of sight within a  $6 \times 6$  window of CCD array independently of the steering mirror control loop, has not yet been built and used in the demonstration. Instead, the effect of telescope gimbal was simulated by keeping the amplitude of beacon jitter within a  $6 \times 6$  window on the CCD array. Closed loop control of the point-ahead angle was demonstrated by specifying a desired point-ahead angle, applying jitter to the beacon laser, and pointing of the transmit laser with the desired point-ahead angle. Performance characterization of the pointing control loop is in progress.

#### 5. CONCLUSION

In conclusion, the design of a laser pointing control loop based on a high frame rate CCD array and a steering mirror was presented. The technique provides closed loop control of the point-ahead angle, and uses a single detector and a single steering mirror for precision beam pointing. A laboratory demonstration of the CCD-based pointing control loop was described.

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## 7. REFERENCES

1. C. C. Chen, H. Ansari, and J. R. Lesh, "Precision beam pointing for laser communication system using a CCD-based tracker," *OE/Aerospace 93*, SPIE Proceedings, Vol. 1949-15, 1993.
2. C. C. Chen and J. R. Lesh, "Overview of the optical communications demonstrator," *OE/Lase 94*, SPIE Proceedings, Vol. 2123, 1994.
3. H. Ansari, "Digital control design of a CCD-based tracking loop for precision beam pointing," *OE/Lase 94*, SPIE Proceedings, Vol. 2123, 1994.
4. H. Ansari and D. Russell, "Highly accurate tracking system for a laser communications link," *OE/Aerospace sensing 94*, SPIE Proceedings, Vol. 2221, 1994.
5. G. F. Franklin, J. D. Powell, and M. L. Workman, *Digital Control of Dynamic Systems*, Second Edition, Addison-Wesley, 1990.
6. "A Study to Define the Impact of Laser Communication Systems on their Host Spacecraft", Hughes Aircraft Co., Final Report NASA-CR-175272, 1984.
7. M. Wittig, L. Van Holtz, D.E.L. Tunbridge, H.C. Vermeulen, "in-Orbit Measurements of Microaccelerations of ESA's Communication Satellite OLYMPUS", *IJcc-Space Laser Communication Technologies 11*, SPIE Proceedings, vol. 1218, 1990.

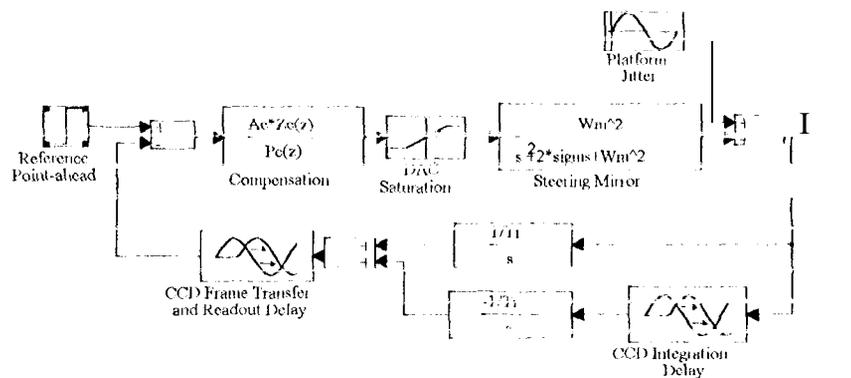


Fig. 1 Block diagram model of the CCD-based pointing control loop.

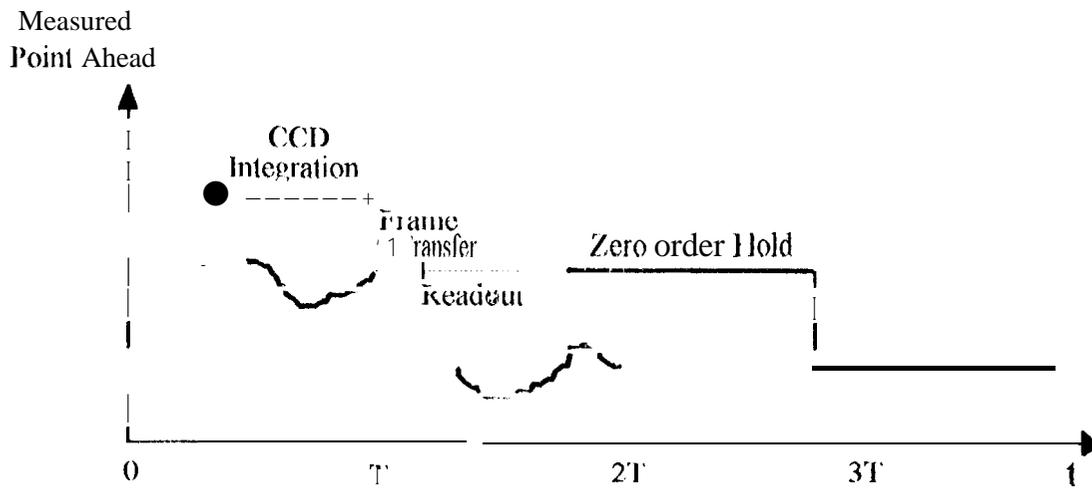


Fig. 2 Timing diagram of the pointing control loop. T is the control loop sampling time.

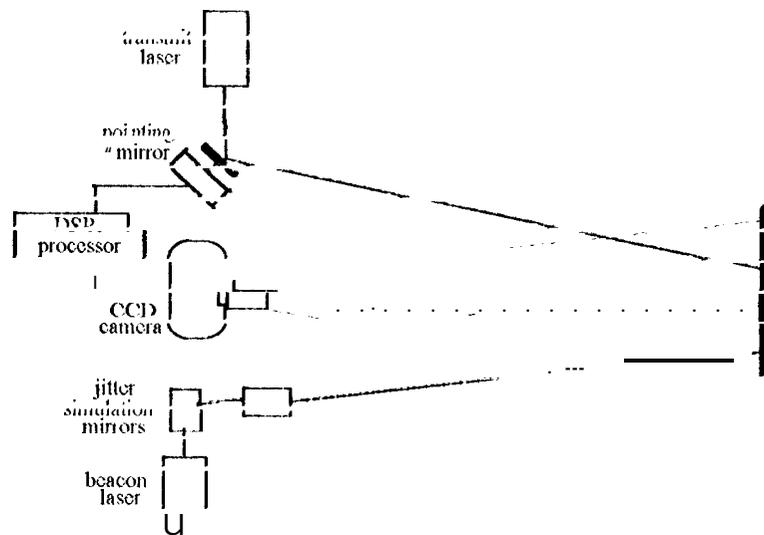


Fig. 3 Simplified block diagram of laboratory demonstrator of pointing control loop.