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Optical Communication System with Range and Attitude Measurement Capability

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A formation optical range and attitude sensor is being developed that uses a laser beam source and a modulated retro-reflector (MRR) target to measure distances between a few meters and a few kilometers with sub-millimeter resolution. Data extracted from multiple MRR targets on a single spacecraft will also provide arcminute-accuracy attitude information with over a ±10-deg field of view. Information encoded on the MRR allows a communication channel to be added to the ranging signal. A laboratory prototype demonstrated a ranging resolution of 0.2 mm with an absolute accuracy of ±2 mm over 2 m.

I. Introduction

A standard ranging technique used, for example, in Global Positioning Systems (GPS) involves cross-correlating a long pseudo-random bit stream (PRBS) pattern referenced to an accurate absolute timing clock with an identical PRBS pattern from another source located at another position with its own accurate absolute timing clock. If one source broadcasts its PRBS pattern to the other, the receiver sees a time delay between the start of its own reference PRBS pattern and the start of the received PRBS pattern, due to the time of flight. Moreover, the time delay is easily extracted using cross-correlation techniques, even in the presence of noise on the received signal.

In this current formation optical range and attitude (FORA) configuration, a laser beam is used to broadcast the PRBS pattern as an amplitude modulation (AM) of the laser intensity. The beam is retro-reflected from a corner cube on the object whose range must be determined. The start of the returned signal's PN sequence is shifted in time from one that is promptly reflected from the emitter by a delay equal to twice the time of flight. Since the received and transmitted signals are synchronized to the same clock and sequence generation trigger, the clock stability must be maintained only for a time period equal to the time of flight. Moreover, an improvement in ranging accuracy can be made by sequentially averaging each periodic PRBS pattern until a suitable signal-to-noise ratio is attained. This eliminates the need for very stable clocks that must maintain the synchronization between the transmitter sequence generator and the receiver sequence generator.

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The recent development of the modulated retro-reflector (MRR) based on a multiple quantum-well semiconductor-technology shutter allows the reflectivity of a corner cube to be varied with bandwidths greater than 1 MHz and extinction ratios greater than 6 dB [1]. This can be used to encode a communications signal on the light reflected from an MRR. The Optical Communications Group at JPL currently is developing a combined optical range and attitude sensor with communications capability that can be used in multi-satellite formation flying networks. The FORA sensor performance eventually will be verified in a dynamic test environment provided by the Terrestrial Planet Finder (TPF) Formation Control Test Bed (FCT).

The difference in range from multiple MRRs spaced at different locations on a targeted spacecraft can be used to provide attitude information of the targeted spacecraft. Sub-millimeter ranging resolution and corner-cube spacing on the order of tens of centimeters on the targeted spacecraft will provide subarcminute attitude resolution. The field of view (FOV) of the transmit laser is limited by the power necessary from the retro-reflected beam to make the required ranging measurement and to meet the bit-error rate (BER) requirements of the transmitted data signal. While the inverse fourth power law dependence of the retro-reflected signal limits the effective range at which this type of system can operate, a wide FOV for the transmit laser and the retro-reflective property of the corner cube greatly reduce the pointing and tracking requirements.

This article describes the performance of the ranging and attitude measurement capability of the FORA sensor and some communications demonstrations.

II. Conceptual Design

Figure 1 gives a block diagram sketch of the ranging system. The laser source is a 980-nm diode laser that is temperature stabilized in order to match its wavelength to the maximum extinction ratio wavelength of the MRR. It has a maximum output power of 100 mW that is collimated into a beam with

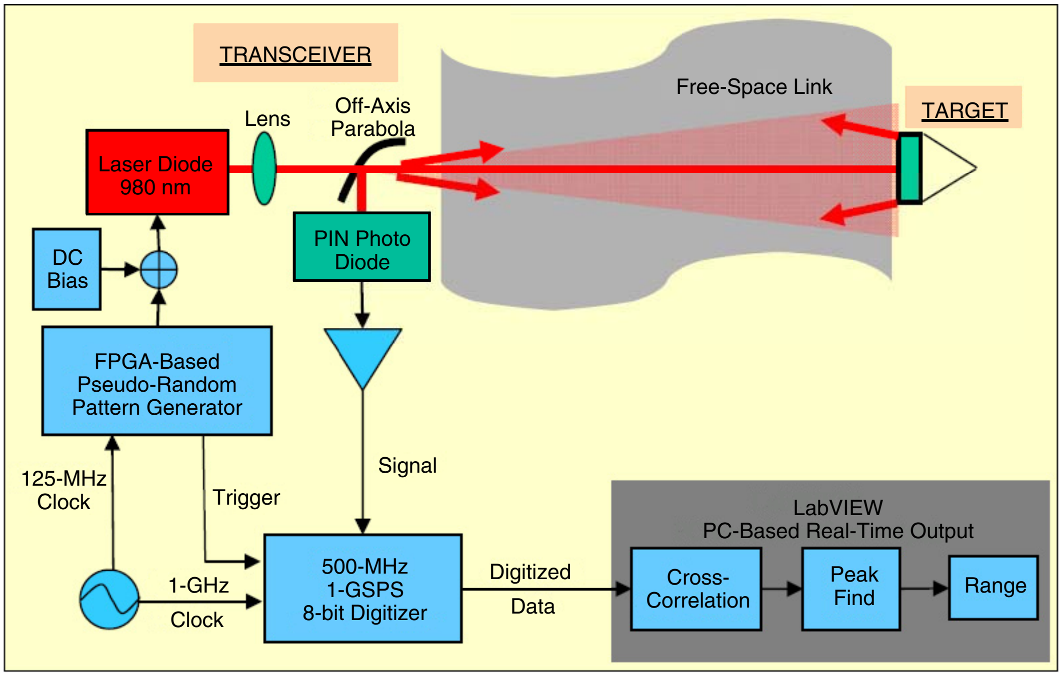

Fig. 1. FORA sensor architecture.

a divergence of about 7 deg. The diode is DC-biased with 70 mA and modulated by a PRBS pattern signal that is AC-coupled through a bias tee network to produce a maximum current of 140 mA and a minimum current of 30 mA near the lasing threshold current.

A 7000-bit-long PRBS pattern is produced by a field-programmable gate array (FPGA) modulator on a peripheral component interconnect (PCI) interface board with a JPL-designed serializer to provide a 500-MHz modulation bandwidth. A 1-GHz external master clock provides a synchronized 125-MHz timing signal for the FPGA. This same clock provides the 1-GHz timing signal for the digitizer. A trigger output denotes the start of each PRBS pattern and is used to trigger the digitizer for the received signal.

The MRRs are the result of a Naval Research Laboratory (NRL) technology development and have been purchased by JPL for evaluation and optical communications applications. The MRR has a clear aperture of about 6 mm, a maximum modulation extinction ratio of about 6 dB, and a bandwidth of about 10 MHz.

The detector is a large area positive intrinsic negative (PIN) photodiode that is operated in a depleted mode and reverse biased at 100 V to maximize its frequency response to about 500 MHz. The detected signal is amplified by 30 dB.

The laser beam is transmitted through a hole in a 51-mm off-axis parabolic reflector (see Fig. 2). The parabolic reflector collects the retro-reflected spots from an MRR that is up to 2 meters away from the laser source (see Fig. 3). The light from the MRR is imaged on the photodetector. This gives the 3-mm photodetector a 4-deg field of view. Two MRRs spaced 13-cm apart from each other are used for demonstration of the attitude measurement (see Fig. 4).

The received signal is acquired and digitized by a 500-MHz to 1-giga-sample/s (GSPS) PCI interface card that uses the same 1-GHz master clock as the PRBS generator. The data processing takes place on a PC-based platform using a LabVIEW Virtual Instrument (VI) software module to deliver real-time data streams with an update rate of a few hertz.

Each digitized data stream set is 2^{16} samples long and is averaged 10 times. This PRBS pattern signal is cross-correlated with a reference PRBS pattern taken at a fixed and known reference position. The

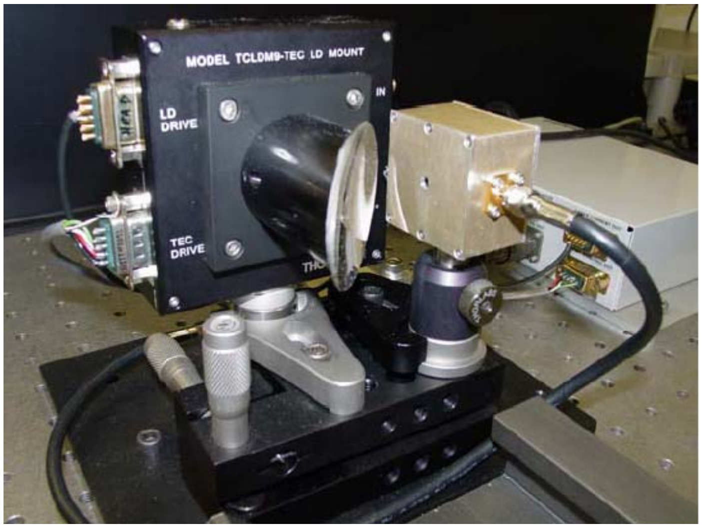

Fig. 2. Laser transmitters and receiver.

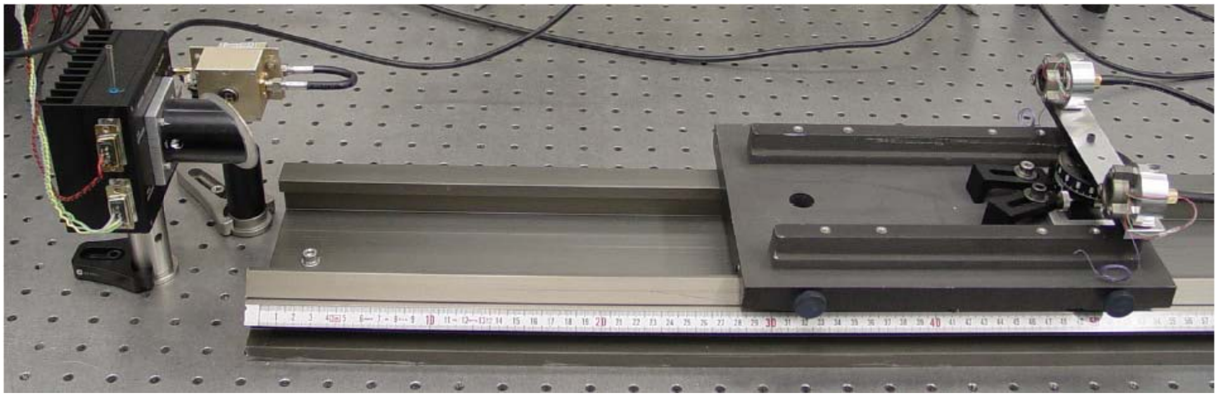

Fig. 3. FORA test setup.

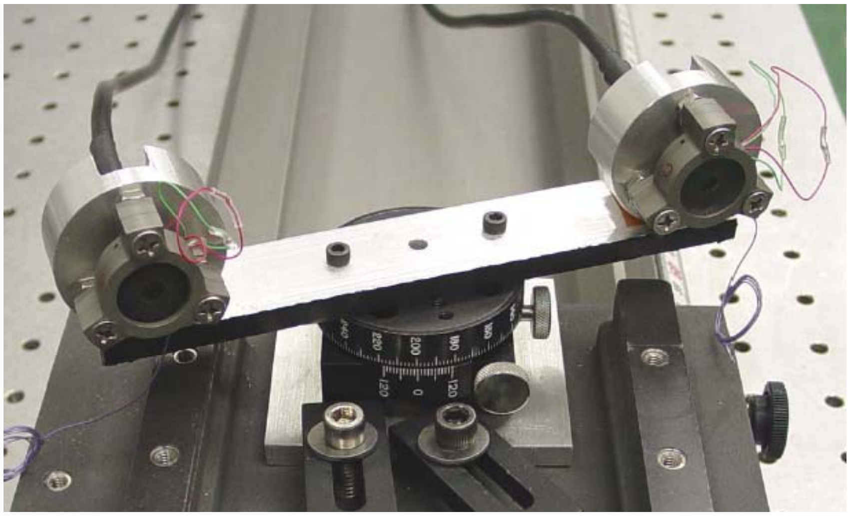

Fig. 4. Setup for attitude measurement with two MRRs spaced 13-cm apart.

cross-correlation uses a standard algorithm based on fast Fourier transform (FFT) techniques. The peak of the cross-correlation output then is fitted to a Gaussian function, and the center position is interpolated to produce a time of flight and, hence, range with sub-millimeter precision.

III. Results

The sensor can currently provide a range measurement with a sub-millimeter measurement resolution and a sub-millimeter absolute accuracy over short distances (100 mm) and times (minutes). Drift in various parts of the analog electronics chain and systematic frequency jitter effects cause the absolute accuracy to be reduced to a few millimeters over longer times (tens of minutes) and distances (1000 mm). This degradation in accuracy should be eliminated with improvements in electronic design. Figure 5 shows the drift in equivalent measured distance for just the clock and PRBS pattern generator and the drift for the full metrology chain ranging to a fixed target. The rms error over short times is 0.2 mm, which gives the measurement resolution.

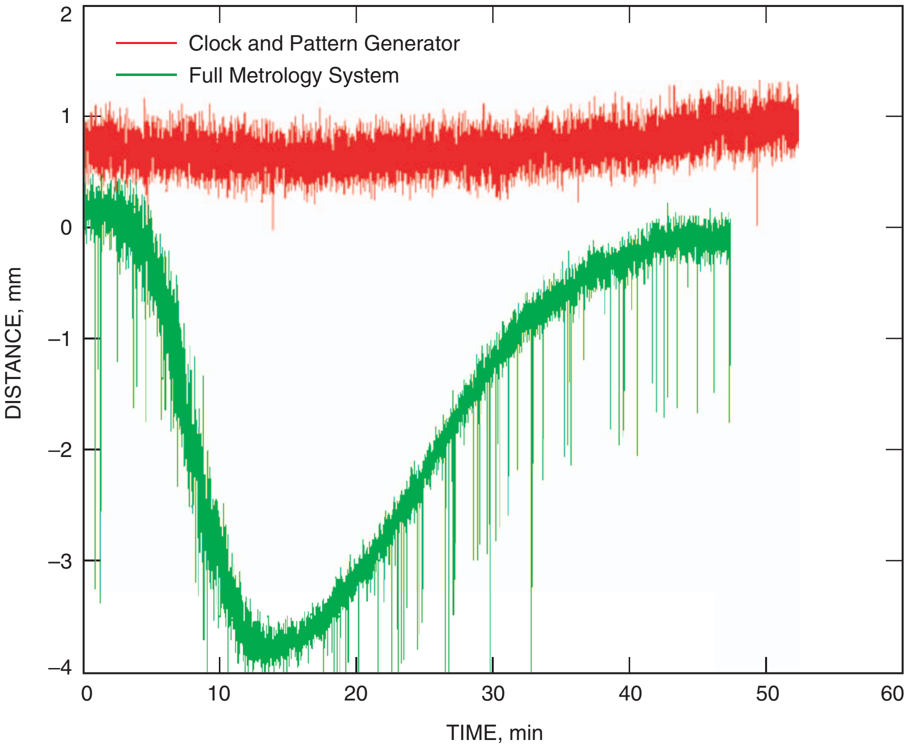

Fig. 5. Stability of the range measurement for PRBS pattern only and full metrology system ranging to a fixed target.

Figure 6 shows the measured range and the actual range. Figure 6 also shows the difference between the measured range and the actual range. There is a systematic error with a period of about 2 m that corresponds to some frequency jitter introduced by the 125-MHz clock. Improvements in the PRBS pattern generation hardware should reduce this effect.

The attitude measurement was tested using two MRRs spaced 13-cm apart at a distance of 2 m from the laser transmitter. The range to each MRR was measured separately. This difference in range to each individual MRR divided by the separation gives the sine of the attitude angle.

Figure 7 shows a plot of the measured angle and its error. The dynamic range of the angle measurement is ±8 deg and is limited by the field of view of the MRR aperture. The resolution is ultimately limited by the resolution of the range measurement and the span separating the two MRRs. In this case, the resolution limit would be 0.1 deg. The measured resolution was 0.7 deg, which was mostly due to how well the retro-reflectors in each MRR were aligned relative to each other.

Combined ranging and communications capability also was demonstrated in this system. A video data stream was transmitted by applying a 5-MHz analog video signal directly to the MRR with an appropriate gain and offset to achieve the full extinction of the MRR reflectivity. A clear visual video stream was produced at the receiver without a reduction in the ranging system performance. In a separate test, only the communications capability of an MRR-based system with a 240-mW, 980-nm diode laser was measured with data rates up to 10 Mb/s and a BER less than 10^{-6} for up to a few meters range.

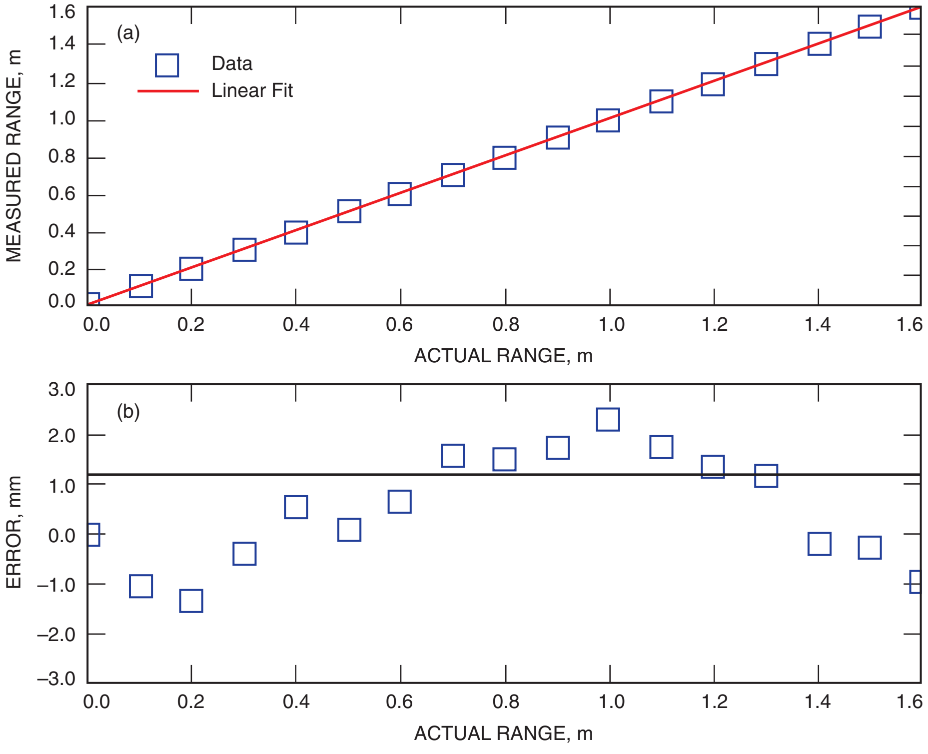

Fig. 6. Results: (a) measured range over 2 m and (b) absolute error over a 2-m range.

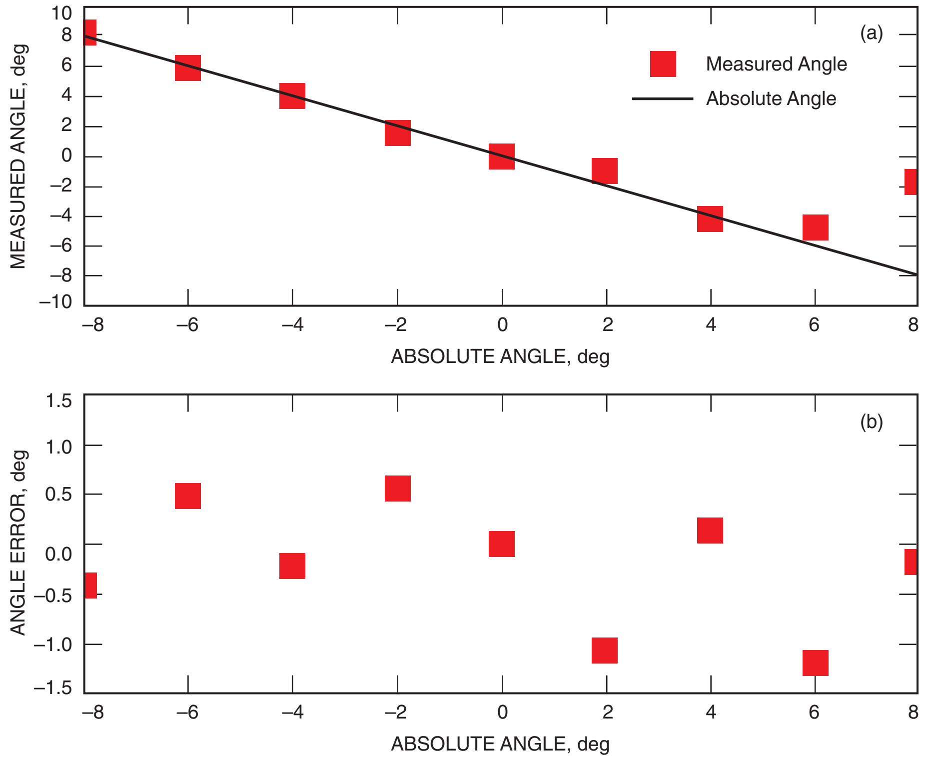

Fig. 7. Results: (a) attitude measurement and (b) error.

IV. Conclusions and Future Work

A pseudo-random bit-stream pattern amplitude modulation for a laser signal retro-reflected off a target produces a real-time ranging signal using a cross-correlation technique. A laser ranging sensor with this scheme was developed with a resolution of 0.2 mm and an absolute accuracy of ±2 mm over 2 m. An attitude sensor using two retro-reflectors 13-cm apart had a measured resolution of 0.7 deg.

Future plans include improving the ranging measurement drift and absolute accuracy, designing a real-time attitude measurement system, increasing the processing speed using faster signal processing platforms, and defining a communications protocol. An integrated system for range, attitude, and communications will be tested on an air-bearing-based free-floating robotic platform at the Formation Control Testbed at JPL.

Reference

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