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**Final CRADA Report
for
CRADA Number Y-1294-0307**

**ADVANCED COMPACT LASER SCANNING SYSTEM
ENHANCEMENTS FOR GEAR AND THREAD
MEASUREMENTS**

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April 04, 1997

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Abstract

The measurement, or metrology, of physical objects is a fundamental requirement for industrial progress. Dimensional measurement capability lies at the heart of our ability to produce objects within the required technical specifications. Increasing performance demands in turn require advances in dimensional measurement technology. In turn, enhanced measurement capabilities make possible the evolution of system designs that can include tighter (smaller) dimensional tolerances. The evolutionary progress of measurement and manufacturing technologies is inextricably lined.

Dimensional metrology systems are presently dominated by touch-probe technologies, which are mature and reliable. Due to the intricate geometries required in certain fields of manufacturing, these contact probes cannot be physically brought in proximity to the measurement surface, or lack sufficient lateral resolution to satisfactorily determine the surface profile, which can occur in the measurement of gears, splines and thread. Optical probes are viable candidates to supplement the contact probes, since light can be focused to less than one micron (40 microinches), no contact occurs that can mar highly finished surfaces, and no probes must be replaced due to wear. However, optical probes typically excel only on one type of surface: mirror-like or diffuse, and the optical stylus itself is oftentimes not as compact as its contact probe counterpart.

Apeiron, Inc. has pioneered the use of optical non-contact sensors to measure machined parts, especially threads, gears and splines. The Oak Ridge Metrology Center at Oak Ridge Y-12 Plant are world-class experts in dimensional metrology. The goal of this CRADA is to tap the expertise in Oak Ridge to evaluate Apeiron's platform, and to suggest new or novel methods of optical surface sensing, if appropriate.

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1. Objectives of the CRADA

The objectives of the CRADA were to determine the resolution limitations of a laser scanning coordinate measurement system and to identify methods of overcoming those limitations. These types of systems can be applied to the emerging applications for high resolution measurements of precision mechanical components such as gears and precision bearings. Specifically, the objectives for both the Contractor and Participant are listed below.

1.1 Contractor Objectives/Tasks

1. Evaluate optical sensor limitations associated with the present sensor technology including resolution limits and error sources.
2. Identify enhancements to the present laser scanning sensor technology and implementation for resolution improvement and error source rejection.
3. Evaluate the measurement uncertainty arising from fixturing, mechanical, and thermal influences and identify strategies for reducing these uncertainties.
4. Jointly prepare the final report summarizing the research findings into a comprehensive set of strategies for measurement system improvements.

1.2 Participant Objectives/Tasks

1. Provide an error budget analysis of the existing laser scanning coordinate measuring system.
2. Provide optical system sensor hardware for testing in Oak Ridge and assist with the design, implementation and analysis of the system tests.
3. Participate in the development, implementation, and analysis of experiments to evaluate the influences due to fixturing, mechanical, and thermal effects associated with the measurement uncertainty.
4. Jointly prepare the final report, with input related to the meaningful implementation of results obtained during the research, experimentation and analysis.

1.3 Success in Meeting the CRADA Objectives

All the CRADA objectives were met or exceeded. Details can be found in Section 3 of the Technical Discussion.

2. Benefit to DOE

Accurate dimensional metrology is vital to DOE's ability to perform its mission with regard to existing and anticipated Defense Programs. While contact probe technologies have been the workhorse for dimensional metrology, optical non-contact methods are superior when no contact with the sample can be tolerated (protection of surface finish, static electricity, etc.), when the measurement surface is inaccessible to a contact probe, or when superior lateral resolution with respect to surface features is required. By combining

(2)

$$\begin{aligned}
I(t) &= |E_1 + E_2|^2 \\
&= a_1^2 + a_2^2 + 2a_1a_2 \cos[(\omega_1 - \omega_2)t + (\phi_1 - \phi_2)] \\
&= a_1^2 + a_2^2 + 2a_1a_2 \cos[\Delta\omega t + \Delta\phi]
\end{aligned}$$

and we detect a different or beat frequency shifted in phase. A sum frequency also is produced, but cannot be detected by the square law detector since it exceeds the detector's bandwidth. Even with the difference frequency, care must be taken to design a system in which the beat frequency can be detected within the bandwidth of available photodiodes. Heterodyning is the basis of this measurement technique, which is explored in more detail in the next section.

3.2.2 The Radar Measurement Equation

The theory of frequency modulated (FM) laser radar and its use to measure distances is straightforward, and it explained succinctly in an article by Everett.¹ A continuous wave (CW) laser frequency is linearly modulated ("chipped") by a triangular wave about its mean frequency such that the modulated signal is given as:

$$f(t) = f_0 + at \quad (3)$$

where f_0 is the mean laser frequency and a is the linear modulation rate in frequency/second, and t is the time variable. A beam splitter redirects a position to the heterodyne detector to form the local oscillator (LO). The remainder is focused by the optical system onto the target surface, is reflected (or absorbed and scattered) and arrives at the receiver after τ seconds, where τ is defined as:

$$\tau = 2 \frac{d}{c} \quad (4)$$

with d the distance to the target surface, and c is the speed of light. The returning signal is optically mixed with the LO on the detector and produces a sum and difference beat frequency (BF). Figure 1 shows the incident wave with its linear or chirped frequency characteristics, and the delayed version

¹ Everett, CDR H.R., "Survey of Collision Avoidance and Ranging Sensors for Mobile Robots," *Robotics and Autonomous Systems*, 5, 5-67 (1989).

returned from the target. Only the difference frequency can be optically detected since only it falls within the detector's bandwidth. The result is:

$$BF_{diff} = f(t) - f(t + \tau) = f_0 + at - (f_0 + a(t + \tau)) = -a\tau \quad (5)$$

and substituting Eq. 4 for τ we have:

$$BF_{diff} = a \left(2 \frac{d}{c} \right). \quad (6)$$

Figure 2 shows the beat frequency versus time due to the incident and return signal. Finally, one can solve for the distance to the target, d , as a function of the beat frequency and chirp rate:

$$d = \frac{c}{2a} BF_{diff}. \quad (7)$$

For example, from a range of 10 cm, if we can chirp the laser at 10 GHz/ μ s, the beat frequency that results is 6.66 MHz. To resolve a change in distance of 10 μ m requires the ability to discriminate the change in frequency to one part in 10^5 or 666 Hz, since $\Delta d/d = \Delta BF_{diff}/BF_{diff}$.

3.2.3 Sensitivity and System Requirements

3.2.3.1 Laser Diode Requirements

3.2.3.2 Chirp Characteristics

Although most laser diodes can be modulated directly (using a bias-T network commonly used with microwave devices) about a DC setpoint, severe requirements are placed upon the microwave sweep generator in terms of linearity and sweep rate (see Eq.7). If the current of the laser diode is modulated, the laser will change frequency at a value of $\Delta\nu \approx 2$ GHz/mA, which is typical for a Fabry-Perot-type (FP)

buried-heterostructure laser.^{2,3} Two undesirable side effects occur, however. Firstly, the gain curve of a semiconductor laser is quite broad and there is nothing in the simple FP structure that determines mode selection except the spacing of the cavity mirrors. Therefore, under the effects of current turning, the laser hops modes to whatever mode is favored under those conditions of current and temperature. This introduces phase noise and degrades the ranging performance. Secondly, the spectral linewidth of these lasers broadens under current modulation which reduces the coherence length of the device, ultimately limiting the maximum range under which a FMCW radar can operate. An alternative is the use of Distributed Feedback (DFB) lasers, which have much better spectral purity due to the frequency-selective feedback element, the distributed grating which forms part of the laser cavity. Since the reason for DFB lasers is to reduce chirping, as this is undesirable for fiber communications systems (it introduces dispersive losses in the fibers), the rate of chirp as a function of modulation current is much reduced. Some authorities state that the chirping performance is equivalent for FP and DFB lasers⁴, but recent information from one DFB laser manufacturer provides typical frequency chirping figures on the order from 100-300 MHz/mA. There is evidence in the literature for FMCW ranging techniques using both garden variety FP diode lasers and three-terminal, tunable DFB lasers. In the first example⁵ workers reported accuracies of 2 μm at a range of 8 mm. In the second⁶, article, a mirror target was measured with 0.1 μm accuracy at a range of 1.5 m, and a diffuse target at a range of 10 m with an accuracy of 2 cm, resulting in accuracies of one part in 10^7 and one part in 5000, respectively. It should be noted that in the second test the range of 10 m was outside the coherence length of the laser.

3.2.3.3 Coherence Length Requirements

The laser must have sufficient coherence to produce a heterodyne signal after traversing the path length from the laser to the target surface and back to the optical mixer. Coherence length is defined as:

$$L_{\text{coherence}} = \frac{\lambda^2}{2\Delta\lambda} = \frac{c}{2\Delta\nu} \quad (8)$$

which would require a $\Delta\lambda$ of about 0.002 nm for a coherence length of 20 cm, which is easily achievable using diode lasers. With no modulation, a Fabry-Perot type laser can have a typical linewidth of 50 MHz, which infers a coherence length of 3 meters. The DFB laser will have coherence lengths in tens to hundreds of meters.

3.2.4 Basic System Architecture

3.2.4.1 System Overview

The basic system is shown for the prototype below in Figure 3. As can be seen from figure, a compact instrument can be built that does not exceed the coherence length of the laser, especially if a fiber variant is designed. Therefore, we can take advantage of the larger chirp rate and relatively low cost of FP diode lasers as the frequency source. However, care must be taken not to chirp the laser into an operating

² Oserwalder, J. M. and B. J. Rickett, "Frequency Modulation of GaAlAs Injection Lasers at Microwave Frequency Rates," *IEEE J. Quantum Electron.*, QE-16 (3), 250-252 (1980).

³ Agrawal, G. P. and N. K. Dutta, *Long Wavelength Semiconductor Lasers*, (Van Nostrand Reinhold Co., New York, 1986), Chap. 6.

⁴ Agrawal, G. P. and N. K. Dutta, Chap. 7 in *Long-Wavelength Semiconductor Lasers*, (Van Nostrand Reinhold, New York, 1986)

⁵ Beheim, G. and K. Fritsch, "Remote displacement measurements using a laser diode," *Elect. Lett.* 21 (3) 93-94 (1985).

⁶ Burrows, E. C. and K. -Y. Liou, "High resolution laser LIDAR utilising two-section distributed feedback semiconductor laser as a coherent source," *Elec. Lett.* 26 (9) 577-579 (1990).

regime that will cause it to mode hop. Favorable operating regions can be found by temperature tuning the laser first, and then frequency sweeping. It has been reported⁵ that one commercially-available laser can be current tuned about 55 GHz before mode hopping, but this seems optimistic. If we use 20 GHz as a conservative estimate as maximum tuning range, with a tuning sensitivity of 2 GHz/mA, and we can produce linear ramp at 10 mA/ μ s, we can chirp laser at 20 GHz/ μ s. Using a range of 10 cm, a beat frequency of 13.3 MHz will be produced. This sets the bandwidth requirement on our mixing photodiode. A resolution of 10 μ m demands that we determine the frequency to a resolution of 1.33 kHz, and a 1 μ m resolution requires discrimination of 133 Hz.

3.2.5 Performance Of The Prototype

The prototype system utilizing FMCW radar methods was successful in showing that the concept of measuring various surfaces with a coaxial sensor is feasible. Beat frequencies were obtained from both specular (mirror) and diffuse surfaces. In fact, a robust beat frequency was obtained from a black anodized aluminum surface, which showed that all of the surface types typically encountered by Aperion can be measured with this technique. Crude data reduction showed that the resolution of the proof-of-concept systems was approximately 20- μ m. This was obtained by translating a mirror on a micrometer stage while the beat was recorded on a digital storage oscilloscope and the period of a representative portion of the beat signal was measured.

The challenge to exploiting the beat signal is not insignificant, however. The simple theory presented in this technical description assumed linear voltage ramps, linear voltage-to-current conversion, and linear chirping behavior of the laser diode. None of these assumptions are strictly true. Also, the beat signal is not continuous, which makes the naive approach of using a counter useless to determine the beat frequency. Advanced signal processing techniques of recording one period of the beat and Fast Fourier transforming the signal to determine its fundamental frequency is not applicable since the signal is neither stationary in the statistical sense, nor continuous. Also, the slowly-varying intensity modulation is impressed upon the beat frequency, as is seen in Figure 4 and Figure 5. One approach is to low pass filter

out this modulation noise, and to normalize the intensity variations, which was not explored in this CRADA but has shown success by other workers.

Figure 4. Beat signal resulting from photomixing of the LO and return beam.

Figure 5. Power spectrum of the first 16 harmonics of the signal shown at the left. Note the large fundamental at 10kHz, the ramp frequency.

The results of appropriate signal conditioning are shown in Figure 6 and Figure 7. However, these still are ideal cases and due to jitter, phase noise, and other system imperfections, many averaged frames of data would be required for obtaining the desired accuracy. This measurement task seems ideally suited for applying wavelet methods, since the signals are noisy, discontinuous, and non-stationary. There was insufficient time to explore this option in this CRADA, but both Apeiron and Oak Ridge are interested in pursuing this approach if the vehicle can be found for further collaboration.

Figure 6. Chirp signal in the time domain with the intensity modulation and baseband chirp effects removed.

Figure 7. Fourier spectrum of the signal at left showing the much-improved signal-to-noise resulting from signal conditioning.

4. Inventions Resulting from CRADA.

No invention disclosures were submitted during the course of this CRADA.

5. Assessment of Commercial Possibilities

The commercial possibilities of a FMCW-based thread and gear measurement sensor are significant. There is a growing need for measuring internal threads, gears, and splines. The currently-used method of triangulation does not lend itself to a compact measurement head that will fit within the confines of the target measurement surfaces. The FMCW method is coaxial, and amenable to a fiber-based

implementation. Polarization-preserving single-mode fibers are mature-enough to assemble a system with off-the-shelf components, which can then be mated to a custom-designed fiber-coupled sensor head. A bit more work is required in the data reduction area, but the problem appears tractable.

6. Plans for Future Collaboration

Due to the small business status of Apeiron, the possibility of a significant WFO subject seems remote. However, if future DP CRADA possibilities can be identified, even a relatively small (\$50K) CRADA would be sufficient to address the issues that were out of scope in CRADA No. Y-12 94-0307. Additionally, if Apeiron can interest additional partners in this sensor technology, this would be an additional source of funds-in work.

7. Conclusions

The ability of U.S. industry to remain in the forefront of precision-engineered components hinges on the ability to measure what we make. Contact-based coordinate measuring machines, thread sensors and the like are a proven, mature, reliable technology. However, their limitations in accessibility and lateral resolution limit their use in many types of manufacturing applications. Apeiron's pioneering approach to non-contact thread measurement has shown that relatively simple optical sensors can be employed to match the performance of some contact sensors. By collaborating with the Metrology Center within the Oak Ridge Centers for Manufacturing Technology, and a novel sensor based on FMCW laser radar was proposed and prototyped with success. The FMCW laser radar approach seems promising with some additional efforts on data reduction and exploitation, and seems amenable for use as a fiber-based system for measuring internal gears, thread, and splines.

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