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Increasing the operating distance of a phase-shift laser range-finding system by using an active reflector

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ABSTRACT

A new phase-shift laser ranging method is developed by combining the conventional phase-shift ranging and the concept of transponder, in which the passive mirror in a phase-shift laser range-finding system is replaced with an active reflector whose light source power is the same as that at the measurement terminal. As a result, the power of the returned light is inversely proportional to the 2nd instead of the 4th power of the distance being measured. Section 3 indicate that by using the active reflector, the operating distance is dramatically increased without increasing the laser power or lens aperture. With a transmitted power of 20 mW and an aperture of 100 mm, the operating distance increased from 1.5 km to 9.4 km, and a 15-fold range gain can be forecasted for a transmitted power of 1 W. This strongly confirms the suitability of the developed phase-shift method with an active reflector for measuring longer distances.

1. Introduction

Laser range finding is one of the key techniques used in cases such as assembly of large-scale equipment, formation flight of spacecraft, and space exploration. Generally, it can be further divided into pulse ranging, frequency-modulated-continuous-wave (FMCW) ranging, phase-shift ranging, and interferometry [1–4]. Pulse ranging can be applied to measure distances of more than 100 km, with a resolution of millimeter-level [4–6]. By comparison, better resolutions can be achieved by using the other three methods based on continuous-wave (CW). More precisely, FMCW [4,7–9] and phase-shift ranging [4,10–13] can be used to achieve a resolution of several tens of microns or even several microns, while a nanometer-level resolution can be achieved by using interferometry [14,15]. However, long distance (> 1 km) measurement is still a great challenge to a CW ranging system, because of the very low returned light power which is inversely proportional to the 4th power of the distance being measured [1,16].

Therefore, an increase in the transmitted laser power or the optical lens area of the range-finding system proportional to the 4th power of the operating distance could be a possible way to improve the measurement range of a CW ranging system, but it is very expensive in most cases and sometimes even infeasible to do so. For example, inter-satellite baseline measurements of future synthetic aperture radar (SAR) systems require a measurement range of more than 100 km and a resolution of millimeter-level or higher [17–20]; however, the transmitted laser power and the lens aperture of the range-finding system are greatly limited by the volume and the load of the small satellite. Therefore, conventional CW methods will not be effective in such cases.

In addition, in order to improve the measurement range, a transponder had been introduced into an interferometer to realize the “active metrology” [21], in which the target detects the phase of an incoming measuring beam and sends back a locally generated laser beam whose phase is referenced to the phase of the incoming beam. This makes the returned light power inversely proportional to the 2nd instead of the 4th power of the distance being measured [16,21,22]. Similar bidirectional interferometers have been used in GRACE follow-on missions [23,24] and LISA [25–27] to measure distances of more than 100 km or even 5 million km. Although a resolution of nanometer-level or even picometer-level can be achieved, such a system is extremely complex and expensive due to the light-wave phase lock between both lasers used.

In this paper, a new phase-shift laser ranging method is developed by combining the conventional phase-shift ranging and the concept of transponder. The passive mirror in a phase-shift laser ranging system is replaced with an “active reflector” which measures the modulation signal and generates new modulated light whose phase is referenced to the original light. As a result, the power of the returned light (the light received at the

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measurement terminal) is inversely proportional to the 2nd instead of the 4th power of the distance being measured. This results in a substantial increase in the returned light power and enables measurements of much longer distances without increasing the light power or lens aperture of a phase-shift range-finding system.

2. Principle

In the phase-shift method developed, the mirror at the target terminal is replaced with an active reflector, as shown in Fig. 1. Compared to transponder applications, there is no distinction between master and slave lasers because the structures between the measurement terminal and the active reflector are the same, which is more reasonable for systems like SAR. The light transmitted by laser 1 is modulated and then divided by beam splitter (BS) 1: part of the light is received by the avalanche photo diode (APD) 1 at the measurement terminal, the other is transmitted to the active reflector and received by APD 3. The light transmitted by laser 2 is modulated by the electrical signal from APD 3 and is split by BS 2: part of the light is received by APD 4 at the active reflector, the other is transmitted to the measurement terminal and received by APD 2. The phase-shift φ_m between the optical signals received by APD 1 and APD 2 is measured at the measurement terminal, while the phase-shift φ_a between the optical signals received by APD 3 and APD 4 is measured at the active reflector. The phase-shift φ_m contains the range information as well as the additional phase-shift φ_a which is generated inside the active reflector. As a result, φ_m and φ_a are used to determine a distance D as follows:

$$D = \frac{c}{2f_m} \times \frac{\varphi_m - \varphi_a}{2\pi} = \frac{c}{2f_m} \times \frac{\varphi_D}{2\pi}, \tag{1}$$

where c is the light speed, f_m is the modulation frequency, and φ_D is the actual phase shift for the distance measurement.

The modulation signal of the active reflector is produced through filtration and amplification of the signal carried by the measurement beam, i.e. the phase information of the modulation signal is reserved while the light power is dramatically enhanced at the active reflector. In the process of signal conversion between optical and electronic domains inside the active reflector, an additional phase shift φ_a is generated, measured inside the active reflector, and sent to the measurement terminal for real-time compensation. The intensity of the signal received by APD 1 is expressed as follows:

$$I_1(t) = I_{a1} \cdot [1 + m \cdot \sin(\omega_m t)], \tag{2}$$

where I_{a1} is the average intensity received by APD 1, m is the modulation amplitude and ω_m is the modulation angular frequency. The intensity of the signal received by APD 3 is expressed as follows:

$$I_3(t) = I_{a3} \cdot \left\{1 + m \cdot \sin\left[\omega_m \left(t + \frac{t_D}{2}\right)\right]\right\}, \tag{3}$$

where I_{a3} is the average intensity received by APD 3, t_D is the time delay generated by the round-trip flight of the signal. At the end of a series of photoelectronic conversions inside the active reflector, the signal carried by the returned light has an additional phase shift φ_a. The intensity of the signal received by APD 4 is expressed as follows:

$$I_4(t) = I_{a4} \cdot \left\{1 + m \cdot \sin\left[\omega_m \left(t + \frac{t_D}{2}\right) + \varphi_a\right]\right\}, \tag{4}$$

where I_{a4} is the average intensity received by APD 4. The returned light is received at the measurement terminal, and the intensity of the signal received by APD 2 is expressed as follows:

$$I_2(t) = I_{a2} \cdot \{1 + m \cdot \sin[\omega_m(t + t_D) + \varphi_a]\}, \tag{5}$$

where I_{a2} is the average intensity received by APD 2. The phase shift φ_m is measured between I_1 and I_2 at the measurement terminal, while the phase shift φ_a is measured between I_3 and I_4 at the active reflector. From both phase-shifts the distance D can be calculated using Eq. (1).

The main factor that limits the operating distance of a phase-shift laser ranging system is the power of the returned light. In conventional methods, the attenuation of returned light power is proportional to the 4th power of the distance being measured. In the proposed method, the optical system of the target terminal is symmetrical to the system of the measurement terminal and the two laser sources have the same transmitted light power. As a result, the attenuation models of measurement light and returned light are the same. The calculated power of the returned light is expressed as follows:

$$P_r = P_t \cdot m \cdot \eta \cdot \frac{d^2}{\theta^2} \cdot \frac{1}{D^2}, \tag{6}$$

where P_r is the received light power, P_t is the transmitted power of the laser light, η is the system transmittance, d is the aperture of a receiving optical lens, and θ is the divergence angle of the laser beam. Moreover, the attenuation of the laser light power (A) and the required transmitted power (P_D) can be expressed as follows:

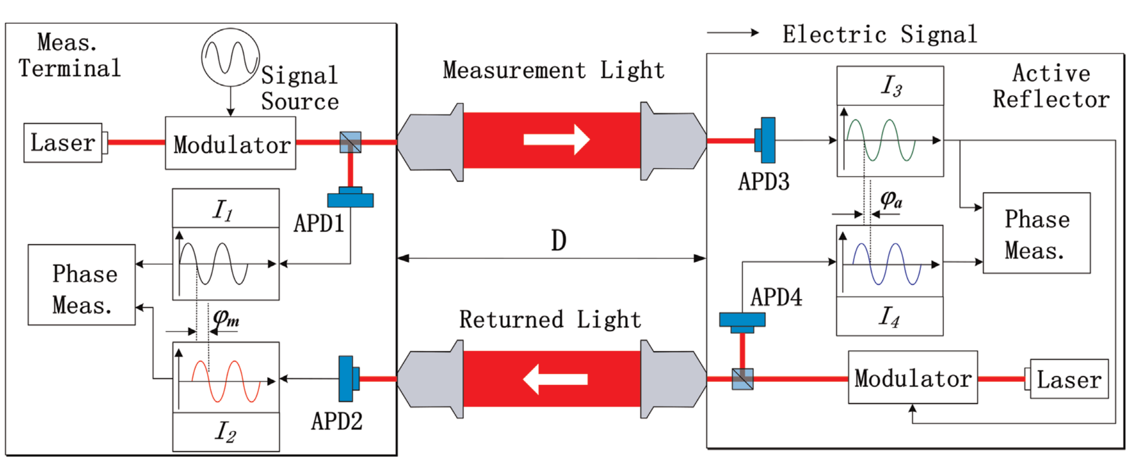

Fig. 1. Structure of the range-finding system with an active reflector.