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Discussion

High-resolution three-dimensional active imaging with uniform distance resolution

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ABSTRACT

We present a method to ensure uniform distance resolution distribution of three-dimensional (3D) active imaging and to improve distance resolution. Rising and falling edges were employed to encode the object depth, which has a uniform distance resolution distribution when the laser pulse shape is Gaussian. The 3D method uses a pulsed laser as the flood illuminating source and an intensified camera as the receiver. A scene at a 50 m distance was detected at a resolution of about 0.1 m, which is about three times better than that obtained by using the conventional method.

1. Introduction

In long-range active imaging, light backscatter reduces image quality considerably [1]. Gated viewing techniques with synchronous ultrashort laser pulses and ultrafast shutters can efficiently remove light backscatter. With rapid progress in highly sensitive image sensors and high-power light sources, gated viewing has been applied to different areas, such as long-range observation [2–4], fog or camouflage nettings penetration [5,6], and underwater target identification [7,8]. This technique can be developed to obtain the depth information of objects, that is, three-dimensional (3D) imaging.

For depth scanning with gated imaging, the time-slicing method [9–11] requires tens of gated intensity images to obtain one 3D image. The large amount of data limits detection speed and the detection of fast-moving objects. Gillespie investigated the intensity to range profiles by correlating the profiles of the laser pulse and the receiver gate [12]. Based on the intensity correlation analysis, Laurenzis et al. proposed a super-resolution method [13] to improve detection speed and decrease data processing time. This method needs a minimum of two gated intensity images to generate one 3D image. It uses a relatively high signal-to-noise ratio (SNR) to subdivide the detection range and increase the detection speed. At a certain SNR, the distance resolution is poorer if the detection range is larger, and vice versa.

To enlarge the depth range and maintain the distance resolution, the coding method [14,15] has been used, in which the number of intensity images increases linearly, and the depth range increases exponentially. Many methods for improving the distance resolution, such as the Lissajous-type eye pattern [4] and noise adoption processing with multiple intensity images, have also been proposed [11,16]. However, all these methods need additional gated intensity images to achieve their advantages.

In this paper, we analyzed the distance error distribution of the super-resolution method and proposed a new method to improve the distance resolution and the distance measurement distributions without additional gated intensity images.

2. Theoretical analysis

The super-resolution method encodes depth information into a range intensity profile because of a convolution of the laser pulse and the receiver gate gain. As depicted in Fig. 1, the laser pulse and receiver gate profiles are rectangular, and the gated image intensity profile is trapezoidal [12,13].

For active gated viewing [2,12], the intensity (per pixel) obtained by the camera is

$$I(z) = \rho z^{-2} e^{-2\tau z} \eta \int G(t + 2z/c) P(t) dt, \quad (1)$$

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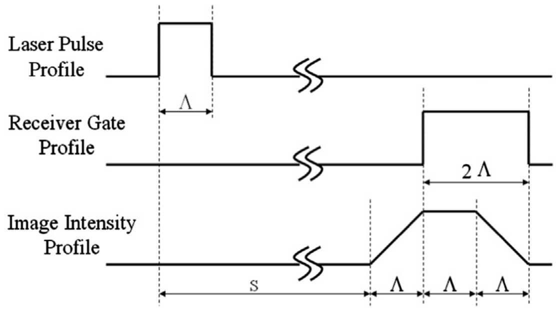

Fig. 1. Laser pulse, receiver gate, and image intensity profiles to the distance of the super-resolution 3D imaging method.

where ρ is a constant related to the target reflectance of the efficient of optical system, z is the target distance, τ is the atmospheric attenuation, η is the effective quantum efficiency of the intensified cameras, G is the gated intensified camera modulation gain function, c is the light speed, and P is the laser power function.

For the super-resolution imaging process, the laser pulse profile is

$$P1(t) = Arect(tc/2\Lambda), \tag{2}$$

where rect is the rectangular function, and $\Lambda = wc/2$, where w is the laser pulse width, and A is the peak power of the laser pulse. The denominator "2" in Eq. (2) indicates that the light pulse goes back and forth from the 3D imaging system and the object.

As depicted in Fig. 1, the super-resolution method decodes the distance from the linear rising or linear falling ramp and the flat top. Two intensity images are needed to form a 3D image. For the super-resolution method, if the rising ramp and the flat top are used, the start gate distance is s for the first gate (flat top) and $s+\Lambda$ for the second gate (linear rising ramp). Therefore, the two receiver gate functions are

$$G1(t+2s/c) = Brect(tc/4\Lambda), \tag{3}$$

$$G2(t+2s/c) = Brect(tc/4\Lambda - 1/2), \tag{4}$$

where B is the gain of the receiver.

Eq. (1) denotes the intensity of the correlation of the laser pulse and the receiver gate profile. According to Eqs. (2)–(4), and given the interested distance range $s < z < s+\Lambda$, the two intensities (for each pixel) are

$$I1(z) = E, \tag{5}$$

$$I2(z) = (z-s)E/\Lambda = z'E/\Lambda, \tag{6}$$

where $E = rz^{-2}e^{-2\tau z}\eta AB$, and $z' = z-s$ is the relative distance.

Given that the active imaging technique employs an ultrashort pulse for both laser and receiver, E can be considered as a constant to a good approximation [2] when $z \gg z'$. Eqs. (5) and (6) indicate that the distance can be decoded from the linear rising ramp and the flat top (linear rising ramp method) as

$$z1 = s + \Lambda I2/I1 \tag{7}$$

If the falling ramp is used, the start gate distance for the second gate is $s-\Lambda$ (linear falling ramp), and the receiver gate function is

$$G3(t+2s/c) = Brect(tc/4\Lambda + 1/2) \tag{8}$$

The intensity is

$$I3(z) = (\Lambda - z')E/\Lambda \tag{9}$$

From Eqs. (6), (8), and (9), the distance that can be decoded from the linear falling ramp and the flat top (linear falling ramp method) is

$$z2 = s + \Lambda(1 - I3/I1) \tag{10}$$

Although numerous noise sources influence the intensities, the photon counting shot noise is the intrinsic noise of light. Based on the static attribute of the Poisson distribution, the shot noises of the intensities are

$$\delta I1 = \sqrt{E/h\nu} = \sqrt{N}, \tag{11}$$

$$\delta I2 = \sqrt{Nz'/\Lambda}, \tag{12}$$

$$\delta I3 = \sqrt{N(\Lambda - z')/\Lambda}, \tag{13}$$

where h is the Planck constant, ν is the frequency of the light, and N is the photon number of a pixel of the receiver.

Eqs. (5)–(13) indicate that the root mean square (RMS) errors of the distances obtained by the linear rising and falling ramp methods are

$$\delta z1 = \sqrt{\left\langle (z1 - \langle z1 \rangle)^2 \right\rangle} = \sqrt{z'(\Lambda + z')/N}, \tag{14}$$

$$\delta z2 = \sqrt{(2\Lambda^2 - 3\Lambda z' + z'^2)/N} = \sqrt{z''(\Lambda + z'')/N} \quad , \tag{15}$$

where $< >$ denotes the average function, $z'' = \Lambda - z$ and it is the complement relative distance.

In Eqs. (14) and (15), the distance distributions are relative to the distance z for the use of the super-resolution method. When $z = s+\Lambda$, the distance detection error is maximum at $\Lambda\sqrt{2/N}$ for the rising ramp decoding method. When $z = s$, the distance detection error is also $\Lambda\sqrt{2/N}$ for the falling ramp decoding method. Further, the distance resolution is strongly related with the distance z.

We noticed that from Eqs. (6) and (9), the distance can be obtained from both the linear rising and falling ramps (both linear ramp methods) also by

$$z3 = s + \Lambda I2/(I2 + I3) \tag{16}$$

Based on Eqs. (6), (9), (12), (13), and (16), the distance error obtained by using both linear ramp methods is

$$\delta z3 = \sqrt{z'(\Lambda - z')/N} = \sqrt{z'z''/N} \tag{17}$$

In Eq. (17), the distance error obviously decreased. The maximum distance error is $\Lambda/2\sqrt{N}$ when $z = s+\Lambda/2$. Both linear ramp methods have a distance resolution that is about 2.83 times better than that of the super-resolution method, in which the maximum distance error is $\Lambda\sqrt{2/N}$.

Although both linear ramp methods improved the distance measure distribution, the distribution is still related to the distance z. A nonlinear intensity to distance relation should be introduced. To find the best distance resolution, the calculus of variations was employed. The minimal distance errors can be obtained by the following intensity to distance profile functions:

$$I4(z) = [1 + \sin(\pi z'/2\Lambda)]E/2, \tag{18}$$

$$I5(z) = [1 - \sin(\pi z'/2\Lambda)]E/2 \tag{19}$$

The distance is obtained by the following sine ramp:

$$z4 = s + \frac{2\Lambda}{\pi}\arcsin\left(\frac{I4 - I5}{I4 + I5}\right) \tag{19}$$

The distance error is

$$\delta z4 = \Lambda/(\pi\sqrt{N}) \tag{20}$$

According to Eq. (20), the distance error is independent of the distance and is about 4.44 times and 1.57 times better than those of the super-resolution and the double linear ramp methods, respectively.