Design of Underwater Laser Triangulation Ranging System and Monte Carlo Simulation Optimization

Guo-liang XIAO, Da-wei TU* and Xu ZHANG

School of Mechatronic Engineering and Automation, Shanghai University, Shanghai 200072, China

*Corresponding author

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Abstract. The laser triangulation ranging system has the effect of refraction at air-glass-water interfaces when underwater applications are underway, as well as the reduction of the active distance and the deterioration of the image quality of the target reflection point due to the scattering and absorption by the aqueous medium. In order to solve these problems, we started with the principle of laser triangulation and then used the Monte Carlo method to establish a random model of underwater laser transmission based on the theory of radiative transfer. TracePro software was used for ray tracing simulation, thereby to obtain the contrast of the reflection point image. The influences of system parameters such as target distance, laser intensity, baseline distance and objective lens aperture on the contrast were discussed and then the parameters were optimized. Finally, starting from the actual situation and needs of the system, determine the laser light intensity 1W, baseline distance 200mm, imaging objective lens 50mm/F2, to ensure a good target contrast within 6m, thus ensuring the implementation of laser triangulation.

Introduction

As a non-contact photoelectric detection technology, laser triangulation has the advantages of simple structure, high speed, high accuracy and flexibility, etc[1,2]. As we all know, the principle of triangulation is based on the positional offset of the image formed by the laser illumination spot reflection. However, when the triangulation system is used underwater, since the light will refract through different air-glass-water media, the imaging position will change, and the measurement equation will need to be corrected accordingly; in addition, the water medium has strong absorption and scattering. Due to these optical characteristics, the laser is greatly attenuated, resulting in poor imaging quality of the spot on the receiving optoelectronic component, limiting the detection distance and accuracy of measurement. Therefore, the underwater laser triangulation system needs to be redesigned and optimized.

Underwater Laser Triangulation System and Measurement Equation

The laser beam irradiates the surface of the object at a certain angle. Then the reflected light on the surface of the object is converged and formed by the optical system. The position of the measured object changes, causing a corresponding change in the position of the image point. Based on the triangular relationship, the distance value of the object can be obtained. Figure 1 shows the laser triangulation principle and its measurement equation when applied in the air:

\[
y = \frac{-x(s_1-f)}{f \sin \alpha - x \cos \alpha (1 - \frac{f}{s_1})}
\]

(1)

where \(y\) is the distance of the target from the reference plane, \(x\) is the coordinate of the reflection point on the CCD, \(f\) is the focal length of the lens, \(\alpha\) is the angle between the laser and the main optical axis of the receiver, \(s_1\) is the distance between the receiver and the reference plane.
When the object distance is changed, the image distance changed accordingly. In order to make the image point fall on the CCD clearly, the position of the CCD needs to follow the Scheimpflug condition to ensure the reflection point and the object point conjugate, as shown in Figure 2.

Scheimpflug condition [3]:

\[ s_1 \tan \alpha = s_2 \tan \beta \]  

where \( s_2 \) is the distance from the imaging surface to the optical center of the lens, and \( \beta \) is the angle between the CCD and the main optical axis of the receiver.

On the other hand, when the triangulation system is applied underwater, the light refracts through the water-air-glass on the surface of different media, and the measurement relationship also changes. Since the glass is relatively thin and can be ignored, the actual receiving imaging light path is shown in Figure 3.

In the figure 3, \( \alpha_0 \) is the angle between the laser beam and the receiver normal in the air. In the actual underwater environment, the light is deflected and the angle becomes \( \alpha_1 \), according to the refractive index formula:

\[ n_0 \sin \alpha_0 = n_1 \sin \alpha_1 \]  

where \( n_0 \) and \( n_1 \) are the refractive index of the laser in air and the refractive index in water, respectively. According to the geometric and optical relationship in Figure 3, the underwater triangulation measurement equation [4]:

\[ L_p(x) = \sqrt{(n^2 - 1)d^2 + n^2d^2\left(\frac{f}{\tan \alpha_0} + x \frac{f}{\tan \alpha_0} + x\right)^2} \]  

Figure 1. Laser trigonometry schematic. 
Figure 2. Revised schematic. 
Figure 3. Actual light path diagram.
where \( x \) is the spot coordinate, \( n \) is the refractive index of water, \( d \) is the distance between the optical axis of the laser beam and the dominant point (marked as the baseline distance), \( L_p(x) \) is the distance between the underwater target and the detector for the spot coordinate \( x \).

Figure 4 shows that the same offset on the CCD corresponds to different target distances in air and water. Set the refractive index of the water 1.33, the baseline distance 200 mm, the focal length of the lens 50 mm, and the angle between the emitted laser beam and the receiving CCD normal is 7°.

![Figure 4. Target distances at different pixel offsets.](image)

**Monte Carlo Simulation of Image Point Contrast**

Due to the strong absorption and scattering optical properties of the aqueous medium, a large amount of background light interference is formed on the receiver. When the background light intensity reaches a certain level, the target reflection image point becomes blurred or even submerged, which seriously affects the determination of the position of the image point, resulting in a large measurement error. Therefore, the system needs to obtain the image formed by the photoelectric element have a high contrast as much as possible. The contrast is defined as:

\[
C = \frac{I_t - I_b}{I_b} \tag{5}
\]

where, \( I_t \) and \( I_b \) are the intensity of the image point on the photoelectric element and the average intensity of the background light, respectively.

Reflected spot contrast is related to measurement distance, laser intensity, baseline distance, objective lens diameter, etc. Therefore, comprehensive optimization design of system parameters and system performance is required.

The distribution of particles in aqueous medium is random, so the interaction of photons with particles in water also shows randomness. According to the theory of radiation transmission, a stochastic model of underwater laser propagation is established: The propagation of light is understood as the absorption and scattering process of a group of discrete photon streams in an aqueous medium, and supposing the scattering does not change the energy; The interaction of light and water molecules and particles therein is expressed by the absorption coefficient, the scattering coefficient, and the distribution function reflecting the scattering. Simulate the interaction of a single photon with an aqueous medium and obtain the result of the transmission of the entire beam in an aqueous medium by the superposition principle.

Using Monte Carlo method to establish the laser transmission model in water medium, it is necessary to determine the new position of the photon after an interaction with the particles in the aqueous medium, which is specifically decomposed into the determination of the movement step length and the determination of the movement direction. According to the radiative transfer theory, its step length \( s \) can be calculated by Beer’s Law[6]:

\[
s = \frac{-\ln(\xi_1)}{c} \tag{6}
\]

where \( \xi_1 \) is uniformly distributed on 0~1, and \( c \) is the attenuation coefficient of water medium.
The traveling direction of scattered photons is determined by the azimuth $\varphi$ of the photons and the scattering phase function $\beta(\theta)$. The scattering phase function $\beta(\theta)$ is described using the Henyey-Greenstein state function [7]:

$$\varphi = 2\pi \xi_2$$  

$$\beta(\theta) = \frac{1-g^2}{4\pi(1+g^2-2g \cos \theta)^2}$$  

where $\xi_2$ is uniformly distributed on 0~1; $\theta$ is the scattering angle; $g$ is an anisotropic factor, ranging from -1 to 1, representing the ratio of forward scattering and backscattering.

The probability of continuing to scattering after a single interaction has occurred is determined by the single-scattering albedo $\omega_0$ [8]:

$$\omega_0 = \frac{b}{c}$$

where $b$ and $c$ are the scattering and attenuation coefficients of the laser, respectively.

In order to avoid wasting computer resources while tracking the photons, the scattering weight $W_n$ and the threshold $W_t$ are set. Photon trace termination conditions:

$$W_t < W_n = \omega_0^n$$

where $W_n$ is the weight of the photons after $n$ times of scattering.

Repeating the above process, tracking a large number of photons and performing statistics and analysis on the photons entering the receiving field of view, the distribution of photons on the CCD can be obtained.

Using Tracepro software, a simulation model was established according to the geometric relationship shown in Figure 5. Through the definition of the laser light source, the intrinsic characteristics of the aqueous medium, and the target surface scattering model, the interactions of the photons in the water medium are characterized.

After the simulation, the total number of rays $N_i$ at the image point on the CCD, and the number $N_b$ of background light rays due to various reasons, including the backscattered light and the forward scattering of the emitted light and the imaged light in the water medium are obtained. The following formula can be used to calculate the contrast of pixels:

$$C = \frac{N_i-N_b}{N_b}$$

Simulation Results Analysis and System Optimization Design

Figure 6 shows the simulation (only part of the tracing light is shown). It can be seen from the simulation results that the backscattered light that enters the receiver's field of view causes a great deal of interference to the system.
The intensity of the laser light is changed, and the relationship between the change of the laser light intensity and the contrast of the reflection spot is obtained (Figure 7). Set the baseline distance to 200mm and the objective lens diameter to 50mm. Curve 1, curve 2, and curve 3 in the figure correspond to target distances of 5m, 6m, and 7m, respectively. As can be seen from the figure, appropriately increasing the laser light intensity can improve the contrast of the reflected image points. Continuously increasing the light intensity will result in the enhancement of various kinds of scattered light, and the contrast enhancement will no longer be obvious.

The relationship between the baseline distance and the contrast of the reflection spots (Figure 8). Set the laser light intensity to 1W and the objective lens diameter to 50mm. As can be seen from the figure, as the baseline distance increases, the image contrast increases. When the baseline distance increases to a certain extent, the contrast does not substantially increase. This is because the increase in the baseline distance corresponds to an increase in the distance between the receiving light path and the emission light path, which reduces the chance that the backscattered light of the emitted laser light enters the field of view of the objective lens. However, after the baseline distance increases to a certain value, this isolation effect is not obvious.

The relationship between the aperture of the objective lens and the contrast of the reflection spot (Figure 9). Set the laser light intensity to 1W and the baseline distance to 200mm. As can be seen from the figure, the aperture of the objective lens increases, and the image contrast slightly decreases.
According to the previous analysis, it can be seen that increasing the target distance will lead to a sharp drop in contrast; increasing the laser light intensity will slightly increase the contrast of the reflection imaging spot, but the overall attenuation will not change. Excessively increasing the intensity of the laser light will cause the scattered light to be strengthened and interfere with the measurement. Increasing the baseline distance is effective within a certain range. However, due to the limitation of the system volume, the baseline distance should not be too large; the objective lens aperture has little effect on the contrast. Considering the comprehensive trade-off, taking the laser light intensity as 1W, the baseline distance as 200mm, imaging objective lens as F50/F2, the contrast of the reflected image point of the direct-type triangulation ranging system is shown in Figure 10. The system has good measurement results when the measurement distance is 6m. Figure 11 shows the two-dimensional map of the reflected light spot and background intensity on the linear array CCD after optimization of the system parameters (shown in pseudo-color). Figure 12 shows the three-dimensional map of the reflected light spot and background intensity on the linear array CCD with the target distance of 6m.

**Conclusion**

In this paper, a stochastic model of radiative transfer theory based on Monte Carlo simulation is established. The Tracepro software is used to perform ray tracing on imaging light and scattered
light entering the objective lens aperture which determine the image contrast of the target reflected light spot. The relationship between the contrast of the reflected spot image with the target distance, the laser intensity, the baseline distance and the aperture of the objective lens is discussed. It is found that the contrast of the reflected spot drop quickly with the increase of the target distance; the laser intensity increases, the contrast of the reflected spot increases slightly, but quickly saturates; the increase of the baseline distance is very effective only within a certain range and is limited by the system volume while the increase of the objective lens aperture does not change much. Finally, starting from the actual needs of the system, determine the laser light intensity 1W, the baseline distance 200mm, imaging objective lens F50/F2, to ensure the laser triangulation can be effectively implemented within 6 meters.

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