Novel system for modulated lidar parameter optimization

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We present a novel system for parameter design and optimization of modulated lidar. The system is realized by combining software simulation with hardware circuit. This method is more reliable and flexible for lidar parameter optimization compared with theoretical computation or fiber-simulated system. Experiments confirm that the system is capable of optimizing parameters for modulated lidar. Key parameters are analyzed as well. The optimal filter bandwidth is 200 MHz and the optimal modulation depth is 0.5 under typical application environment.

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Lidar has been an efficient tool for remote sensing, but its effective range is often limited by signal-to-noise ratio (SNR)[1−4]. Modulated lidar has been known to be capable of enhancing target contrast and increasing depth for underwater detection[5]. Therefore, this has been widely studied since its proposal in the 1990s[6]. Parameter design has been a critical issue for developing modulated lidar[7] because it considerably affects the system performance. Recently, two methods for parameter design emerged[8]: theoretical computation and fiber simulation. The theoretical computation method has been rendered not accurate enough for practical applications, especially for analog circuit design[9,10]. The fiber simulation method has been shown to lack flexibility because the fiber parameters are limited to a certain range and cannot be changed. Due to this inflexibility, applications of parameter design using the fiber simulation method have been limited.

To solve the conflict between accuracy and flexibility, a novel system for parameter design is presented. The system is composed of simulation software and analog circuit. Parameters can be set and changed by software, and high accuracy is ensured by the analog circuit. Therefore, the proposed system can solve existing problems as well as design and optimize parameters of modulated lidar.

To accomplish flexibility and accuracy, the system is composed of two parts: simulation software and analog circuit. As shown in Fig. 1, echo is simulated and generated by the simulation software and subsequently processed by the analog circuit. By setting environment parameters, the system can be used to design and optimize parameters under various conditions. Moreover, by using the analog circuit, the system keeps in accordance with actual modulated lidar system in signal processing.

Echo is generated by software, which simulates the process of source signal passing through seawater. The echo model consists of the source and channel models[11]. The source model is based on the modulation principle. The channel model is set up by combining backscattering[12] with target signal. The detected echo can be described by

$$P(t) = P_{\rm m}(t) \otimes (H_{\rm b}(t) + H_{\rm t}(t)) = P_{\rm b}(t) + P_{\rm t}(t), \quad (1)$$

where t is the sampling moment, $\otimes$ is the convolution operator, $P_{\rm m}(t)$ is the power function of the modulated laser pulse, $H_{\rm b}(t)$ is the backscattering model, and $H_{\rm t}(t)$ is the target signal model. In the detected echo, $P_{\rm b}(t)$ is the backscatter signal and $P_{\rm t}(t)$ is the target signal. The two can also be expressed as

$$P_{\rm b}(t) = P_0 A \rho_{\rm b} \sum_i \{1 + m\cos[2\pi f_{\rm m}(t - t_i)]\} [u(t - t_i) - u(t - t_n - t_i)]\, {\rm e}^{-2\alpha\nu t_i}, \quad (2)$$

$$P_{\rm t}(t) = P_0 A \rho_{\rm t} {\rm e}^{-2avt_{\rm t}} [u(t - t_{\rm t}) - u(t - t_{\rm t} - t_n)] \{1 + m\cos[2\pi f_{\rm m}(t - t_{\rm t})]\}, \quad (3)$$

where P_0 is the power of laser pulse, t_n is the pulse width, m is the modulation depth, and $f_{\rm m}$ is the modulation frequency. These are parameters of the signal source. For the channel, $A = \eta F A_{\rm r}/R^2$, η is the combined efficiency, F is the interception factor, $A_{\rm r}$ is the effective receiving area of the photo-receiver, $A_{\rm r} = \pi D^2/4$ (D is the

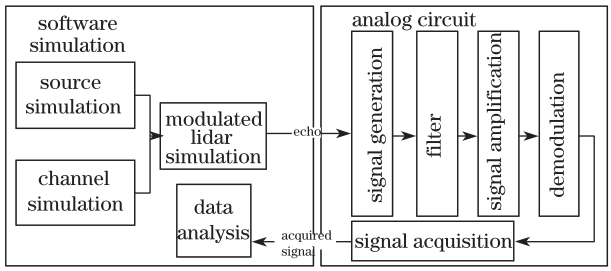

Fig. 1. Block diagram of the parameter design system.

effective aperture of the optical receiver device), R is the distance between the lidar emitter and the scatterer. α is the attenuation coefficient, v is the propagating velocity of light in water, $\rho_{\rm b}$ is the backscattering ratio, $\rho_{\rm t}$ is the reflection ratio of target, t_i is the moment of the ith backscatter, and $t_{\rm t}$ is the moment of target reflection. t_i and $t_{\rm t}$ are counted from the moment that light enters the water. $u(t)$ is the unit step function.

The lidar-detected echo is generated and passed to the analog circuit composed of signal generator, filter, amplifier, demodulator, and data acquisition circuit. System characteristics such as SNR can be obtained by analyzing the acquired echo. In this letter, the optimal design is derived from locating the suitable SNR.

The system construction is shown in Fig. 2. The software is realized on industrial control computer (ICP). It is shown in the block as "simulation control module". This module controls parameters of source and channel, as well as the interface with analog circuit. The software is made up of three parts: source simulation module, channel simulation module, and parameter control interface. Details are shown in Fig. 3.

The source simulation module and the channel simulation module are separately controlled. Their output are combined in the echo generation module, and then transferred to the analog circuit. Waveforms of the echo and the processed echoes are shown in Fig. 4, and the data are finally collected by the record module.

In Fig. 2, the signal generator is used to convert digital echo to analog signal. The digital echo $x(n)$ is generated by software. The analog signal generated with

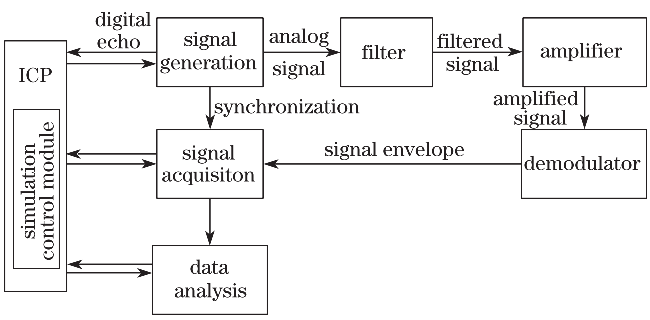

Fig. 2. System structure.

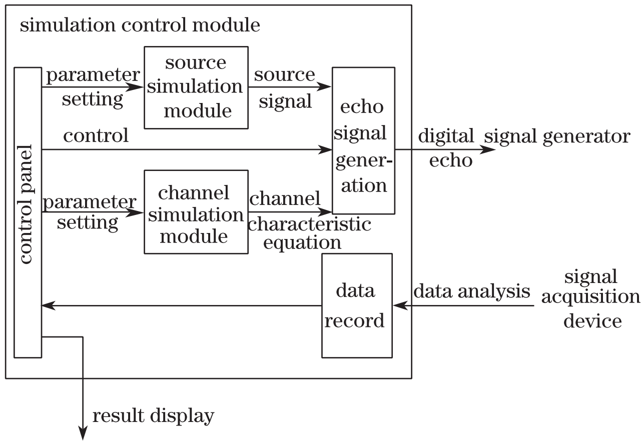

Fig. 3. Structure of software simulation.

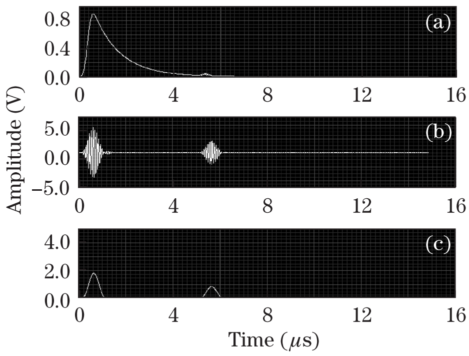

Fig. 4. Waveforms of (a) echo, (b) echo after filtering, and (c) echo after detection.

digital-to-analog (D/A) sampling frequency of $1/T_{\rm s}$ is denoted as $x_{\rm a}(t)$:

$$x_{\rm a}(t)|_{t=nT_{\rm s}} = x(n), \quad (4)$$

where n denotes the $n_{\rm th}$ sample.

The corresponding frequency spectrum of echo is denoted as

$$X({\rm e}^{{\rm j}w})|_{w=\Omega T_{\rm s}} = \frac{1}{T_{\rm s}}\sum_{r=-\infty}^{+\infty} X_{\rm a}({\rm j}\Omega - {\rm j}r\Omega_{\rm s}), \quad (5)$$

where $X_{\rm a}({\rm j}\Omega)$ is analog the Fourier transform of $x_{\rm a}(t)$, Ω is the analog angular frequency, and $w = \Omega T_{\rm s}$ is the digital angular frequency.

In reality, the bandwidth of modulated lidar echo value can be as large as gigahertz (GHz) level. Therefore, the sampling frequency of signal generator should be at least on the GHz level, which is difficult to achieve. However, our system can sufficiently generate the echo with low sampling frequency. Suppose that the actual sampling interval of signal generator is $T_{\rm r}$ and it is larger than $T_{\rm s}$. Then, the actual sampling frequency, which is $1/T_{\rm r}$, is smaller than $1/T_{\rm s}$. The actual output analog signal is denoted as

$$x'_{\rm a}(t)|_{t=nT_{\rm r}} = x(n). \quad (6)$$

By combining Eqs. (4) and (6), we obtain

$$x'_{\rm a}(t) = x_{\rm a}\Big(\frac{T_{\rm r}}{T_{\rm s}}t\Big). \quad (7)$$

Since $x'_{\rm a}(t)$ denotes the actual output analog signal and $x_{\rm a}(t)$ denotes the required analog signal, the actual output analog signal sampled is obviously in lower frequency. $1/T_{\rm r}$ is the linear expansion of the required signal in time domain with expansion ratio of $T_{\rm s}/T_{\rm r}$; its

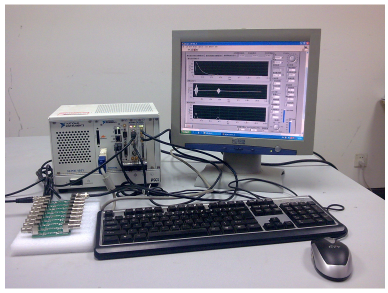

Fig. 5. Photograph of the system setup.

corresponding frequency spectrum is denoted as

$$X'(\mathrm{e}^{\mathrm{j}w})|_{w=\Omega T_\mathrm{r}} = \frac{1}{T_\mathrm{s}} \sum_{r=-\infty}^{+\infty} X_\mathrm{a}\Big[\mathrm{j}\frac{T_\mathrm{r}}{T_\mathrm{s}}(\Omega - r\Omega_\mathrm{r})\Big] = \frac{1}{T_\mathrm{s}} \sum_{r=-\infty}^{+\infty} X_\mathrm{a}\Big[\mathrm{j}\frac{T_\mathrm{r}}{T_\mathrm{s}}\Omega - r\Omega_\mathrm{s}\Big]. \quad (8)$$

From Eqs. (4) and (6), we derive

$$X'(\mathrm{e}^{\mathrm{j}w}) = X(\mathrm{e}^{\mathrm{j}wT_\mathrm{s}/T_\mathrm{r}}). \quad (9)$$

From Eq. (9), we conclude that the actual signal in frequency domain is the linear compression of the required signal, and the compression ratio is also $T_\mathrm{s}/T_\mathrm{r}$. Therefore, processing and analysis of the obtained signal are not affected after the analog circuit is designed by compressing its required frequency spectrum with the same ratio of $T_\mathrm{s}/T_\mathrm{r}$. Through this, the system is implemented with a more stable analog circuit while the result remains unaffected.

The system setup is shown in Fig. 5. The analog circuit and the software platform comprise the following items. IPC platform: including the IPC chassis and the IPC controller which adopt the NI PXI1031 IPC chassis and NI PXI8106 controller in the system, respectively. Signal generator: NI PXI5441 arbitrary waveform generator. Filter: 3-order Butterworth filters group, 9 channels under each single center frequency. Amplifier: OPA842 voltage feedback operational amplifier circuit. Demodulator: SCI0 detector circuit. Data acquisition device: NI PXI5152 high-speed data acquisition board. Software development environment: LabVIEW 8.6.

To verify the reliability of the system, a series of parameters are tested and experiment results are analyzed to find the optimal design. The fixed parameter method is adopted. This means that other system parameters are set to typical values when testing a single parameter and the corresponding experiment data are obtained. SNR is derived by analyzing the obtained experiment data. The suitable value indicates the optimal parameter design. Typical parameter values of the modulated lidar are shown in Table 1.

Among the parameters of modulated lidar, modulation depth and filter bandwidth are the most important ones. Target signal is determined by modulation depth. The extent of noise suppression is determined by filter bandwidth. Therefore, target contrast is directly affected by the two parameters, which are taken as examples and tested in the experiment. Moreover, as another important parameter for channel, attenuation coefficient of seawater is tested and analyzed. Theoretical computation results with respect to the same parameters are provided for comparison.

To study the performance of modulated lidar in various seawater samples, six experiments were carried out with attenuation coefficient α of seawater set to 0.05, 0.1, 0.15, 0.2, 0.3, and 0.35. Theoretical computation is performed under the same parameters. The results are shown in Fig. 6.

In both groups of data, SNR decreases as α increases. α is related with the turbidity of seawater. Therefore, the modulated lidar will achieve better performance in clean water than in turbid water. However, SNR can also be as high as 18 dB even when α is set to 0.35, which proves that the modulated lidar can also be used to improve the target contrast in turbid water.

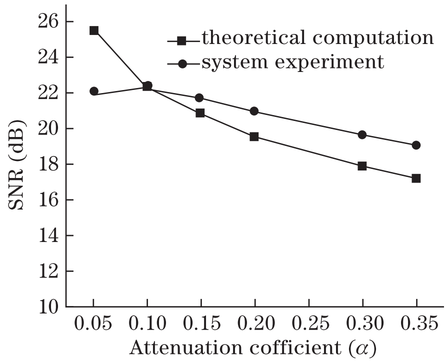

Fig. 6. SNR with respect to attenuation coefficient α.

Modulation depth is also tested and the results are shown in Fig. 7. The system and theoretical computations show different results. The latter is a horizontal line, which means that the modulation depth m does not affect SNR, whereas the former shows that SNR is improved with increasing m. In theoretical computation, the detection model of lidar echo is ideal and thus SNR is kept constant, because it is not influenced by random noise. In practical systems, however, the smaller m is, the smaller the power of target signal becomes. SNR will be influenced more easily by random noise and circuit disturbance. Therefore, the system is guaranteed stable only in the situation where m is set to a value that is large enough. Compared with theoretical computation, our system takes random noise and circuit disturbance into account. Therefore,

Table 1. Typical Parameter Values of Modulated Lidar

Parameter	Value	Parameter	Value
Modulation Frequency	3 GHz	Target Reflection Ratio	0.2
Bandwidth	200 MHz	Target Depth	10 m
Pulse Width	10 ns	Attenuation Coefficient	0.15
Modulation Depth	0.5	Backscattering Ratio	0.0027

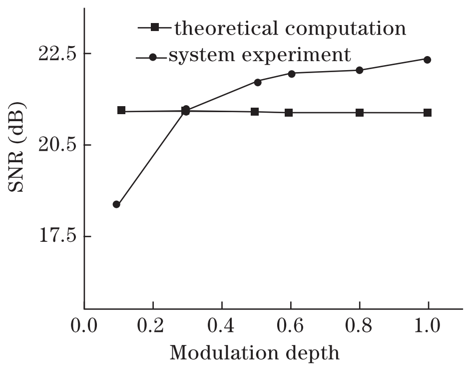

Fig. 7. SNR with respect to modulation depth m.

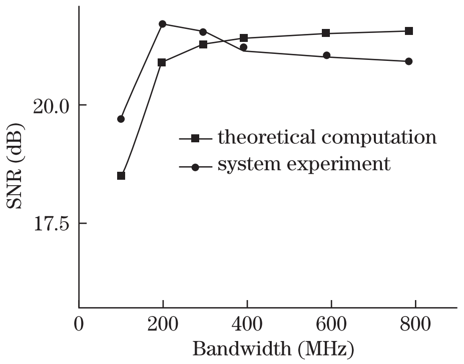

Fig. 8. SNR with respect to filter bandwidth.

it is more reliable. In order to enhance the target contrast, m should be greater than 0.5. However, increasing m over 0.5 will not help significantly in improving the SNR. Therefore, considering the modulator cost, m designed with the value of 0.5 is reasonable.

Filter bandwidth is tested and Fig. 8 shows the results. The tendency of target contrast in system experiment is different from the tendency in theoretical computation when the bandwidth is increased. Theoretical computation results indicate that SNR will increase and then stabilize when the filter bandwidth reaches a certain value. However, the system results indicate that SNR will first increase and then decrease. The cause of this difference is that the target signal with modulation frequency is in high frequency domain and the backscatter noise is mainly in low frequency domain. On the other hand, theoretical computation based on an ideal model showed the absence of noise in between. Therefore, in theoretical computation, the target contrast improves with increasing filter bandwidth. Improvement stops when filter bandwidth grows equal to the bandwidth of the target signal. This is not the case in practical systems where the increase of filter bandwidth results in the increase of unfiltered aliasing random noise along with target signal. Therefore, when the filter bandwidth continues to increase, the target contrast will decrease.

The filter method largely promotes the target contrast, and the target contrast can reach its maximum by adjusting the filter bandwidth. Specifically, setting the filter bandwidth to 200 MHz will optimize the SNR.

In conclusion, we present a parameter optimizing system for modulated lidar. The system is flexible for parameter design, and has been proven reliable based on the comparison with theoretical computation. Parameters of modulated lidar can be optimally designed. Under typical application, 200 MHz and 0.5 are the optimal values for filter bandwidth and modulation depth, respectively.

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