Compressive sampling and gated viewing three-dimensional laser radar

Ximing Ren¹, Li Li, and Ersheng Dang
School of Electronics and Information Engineering, Beihang University, Beijing 100191, P. R. China

E-mail: rxmbit@gmail.com

Abstract. By a new framework named compressed sensing (CS) for the compressive sampling achieving simultaneous sampling and compression of signals, it is possible for us to perform laser imaging using a single detector rather than focal plane arrays having millions of pixels. Moreover, based on acquiring a serial of time-slicing images through combining compressive sampling with gated viewing, the three-dimensional(3D) scene can be reconstructed, wherein a single-pixel gated viewing 3D imaging LADAR system prototype is proposed in this paper; numerical experiments using the proposed 3D image formation model evaluate the system preliminarily and draw the main result that higher range accuracy for 3D scene as the increase of pseudorandom projections by qualitative analysis from Lissajous figures.

1. Introduction

Laser active imaging systems have the advantages of high reliability and spatial resolution, in particular the three-dimensional (3D) laser detecting and ranging (LADAR) systems which obtain full space information [1]. Recently, 3D imaging LADAR systems have drawn a great deal of attention on the use of target detection, recognition and classification [2,3,4,5]. It is common and efficient for most 3D imaging LADAR systems to acquire object’s 3D data through focal plane arrays sensing. However, adapting to image at wavelengths, especially low-light, near-IR or short-wavelength IR imaging, requires expensive sensors, most of which are still in the experimental research stage. Additionally, massive data acquisition and storage in the receivers are required in 3D imaging LADAR systems. To reduce the quantity of imaging data and lessen power consumption, in two dimensional imaging, there is a related research, such as Ma in[6], proposing a single-pixel imaging system for remote sensing.

¹ School of Electronics and Information Engineering, Beihang University, New Main Building F1013, 37 Xue Yuan Road, Hai Dian District, Beijing 100191, P. R. China
Likewise, in order to minimize the 3D imaging LADAR systems, get rid of the dependence on focal plane arrays with special wavelengths, and reduce data storage overhead and energy consumption, as an alternative, we propose a single-pixel gated viewing 3D imaging LADAR system in this paper, based on a new sensing mechanism named compressed imaging\cite{7,8}, which is a revolutionary technology of image generation created by Rice University. And as known from gated viewing \cite{9,10,11,12}, it is used for laser ranging and for overcoming backscatter brought by obscurants by camouflage, fog or water has matured into a robust and efficient method for recovering the surfaces of objects.

The rest of the paper is organized as follows. In the next section, we describe the single-pixel gated viewing 3D imaging LADAR system prototype. In Section 3, we describe the detailed process of 3D reconstruction from time-slicing 2D images. In Section 4, we present our simulations generated by the use 3D image formation model. Section 5 concludes the paper.

2. SYSTEM DESCRIPTION

Our single-pixel gated viewing 3D imaging LADAR system is illustrated in Figure 1. Its sampling mechanism resembles traditional gated viewing. It means that during the pulsed laser travels, the detector gate remains closed, thereby eliminating backscattered light from the light scattering media and improving the system’s SNR. But its distinct feature is that the incident light field from the scene is modulated by the digital micro-mirror device (DMD) \cite{7} before passing the ultrafast shutter, then reaching the single detector. Note that the principle of the gated viewing technology is based on the ability to control the laser beam and the detector shutter in a very accurate way in order to limit the detection to a specific range of space \cite{12}, so the synchronous control technology is applied in this system.

There are two choices in keeping with the synchronization triggered: internal trigger and external trigger. On the one hand, internal trigger mode need delay pulse generator to generate trigger signal source. Then the trigger signal is separately imported into the pulsed laser and the detector shutter from the two delay channel. By control the delay time of two delayed channel respectively. Therefore, pulsed laser synchronize with detector has been achieved. One of the necessary conditions for internal trigger is that the pulsed laser can be controlled by external trigger. In other words, laser which is enabled depends on external trigger signal. In addition, laser light frontier jitter of the pulse laser must be small, and the delay time from receiving trigger signal to producing laser output must be fixed, which means that it is overcritical for the high performance laser. So, this mode is not a good choice. On the other hand, it is the external trigger mode. As depicted in Figure 1, unlike the internal trigger mode, here, the pulsed laser works autonomously. At the same time, the emitted laser is partially into the photodiode, followed converting light to electric signal. Then the electric signal imports into delay pulse generator. The delay pulse generator output trigger delay and the pulse signal width to detector shutter and DMD. Delay time and duty cycle can be regulated by delay pulse generator. Therefore, the detector shutter and DMD can be controlled to open when the emergent light arrived which reflected by the target. It sets delay time based on the range of target.
3. 3D Image Formation Model

The proposed imaging LADAR system can be operated in a specific way in order to produce a set of slicing images of the observed scene which are still reconstructed by compressing imaging. On the basis of three slicing images, a 3D scene reconstruction can be achieved by the algorithm mentioned in[12].

3.1 Time-Slicing Technique based on compressed sampling

Specifically, the mechanism of the proposed imaging LADAR system has two different parts: 1) sensing “hardware”, and 2) reconstructing “software”. The “hardware” is comprised of a synchronizer, an ultrafast shutter, a DMD and a single detector. And the sampling scheme is as same as the one described in[7] and [8]. However, the measurement basis matrix applies a Walsh Hadamard matrix. Meanwhile, there is a synchronized mechanism to ensure acquiring the ranges for the interest scene. Additionally, for the “software”, the reconstruction algorithm uses “Your Algorithms for L1 Optimization (YALL1)” [13].

To be more exact, a permutated Walsh Hadamard matrix A (M*N) generated by the digital DMD is programmed. Here, M is the number of rows and N is number of columns, note that $M \ll N$. In fact, to correctly implement in the DMD, the matrix entries $-1$ and $1$ are shifted to 0 and 1 [14].

In terms of gated viewing active imaging, it is based on synchronization of illumination and image sensor gate. Figure 2 shows how $P(t)$ and $G(t)$ come together to form $I$. It can be depict [12] as:

$$I_i = \int P(t-2r/c)G(t-t_i)dt$$  \hspace{1cm} (1)

where the pulse is delayed by the round-trip travel time $2r/c$ at a range of $r$. The detector gate is delay
by the time \( t_i, i \in \{1, 2, 3\ldots\} \) sequentially. The sequence of time slices or range Gates \( I_i \) is record for all \((x, y)\) pixel, resulting in a data set:

\[
I_i = \{ p_{i1}, p_{i2}, p_{i3}, \ldots, p_{in} \}, \quad n \in \{1, 2, 3\ldots N\}, \quad i \in \{1, 2, 3\ldots\}.
\]

Then in the certain \( t_i \), it is modulated by DMD and measurements in matrix notation can be described as:

\[
Y = AI + \varepsilon
\]  

(2)

where \( \varepsilon \) denotes the possible measurement errors or noises. \( Y \) is an \( M \times 1 \) column vector, denoting in a data set:

\[
Y_i = \{ y_{i1}, y_{i2}, y_{i3}, \ldots, y_{im} \}, \quad m \in \{1, 2, 3\ldots M\}, \quad i \in \{1, 2, 3\ldots\}.
\]

Based on the theory of compressive sensing introduced recently in [15], through a reconstruction algorithm YALL1, \( I \) can be recovered from the measurements \( Y \), and the result corresponding to reconstructed gated images is denoted in a set as:

\[
I'_i = \{ p'_{1i}, p'_{2i}, p'_{3i}, \ldots, p'_{ni} \}, \quad n \in \{1, 2, 3\ldots N\}, \quad i \in \{1, 2, 3\ldots G\},
\]

where \( G \) is the total number of the reconstructed gated images.

3.2 Three Dimensional Reconstruction

With the appropriate gate control, we can obtain a series of images from a gated viewing system in special delay time \( t' = \{ t'_1, t'_2, \ldots, t'_n \} \). These images can be recorded as: \( t' = \{ I'_1, I'_2, \ldots, I'_n \} \).

The task in 3D image is to determine a range value for each pixel. And the round-trip time \( t_r \)
\( (t_r = 2r / c) \) of the laser pulse is proportional to range. So we can use the data set \( \{r_t', t_i\} \) to determine the \( t_r \). As a result, then the range corresponding to each pixel can be achieved. In the standard setup, the detector is gated such that it is open for a time \( t_{\text{gate}} \) and with a time delay after pulse emission of \( t_i = t_0 + i \Delta t \). Here \( t_0 \) is the initial delay, \( \Delta t \) is delay step, the sequence of delays runs \( i = 1, 2, \ldots, T_r \), where \( T_r \) is time slices in the sequence.

\( I_r'(x, y) \) is the gray value corresponding to \( (x, y) \) in the \( i \)th image in a sequence of 2D images obtained from CS-reconstruction. By summing the 2D images \( i = 1, 2, 3, \ldots, G \), so we have follows equation.

\[
I_r = \sum_{i=1}^{G} I_r'(x, y)
\]

Therefore we can calculate the average round-trip time \( \langle t \rangle \) to an object point within the field of view of a pixel.

\[
\langle t \rangle = \frac{2r}{c} = I_{r^{-1}} \sum_i I_i t_i = I_{r^{-1}} \sum_i I_r'(t_0 + i \Delta t) = t_0 + \Delta t I_{r^{-1}} \sum_i i * I_i
\]

Finally, we obtained the distance \( z(x, y) \) to a target point in any pixel.

\[
z(x, y) = \frac{c}{2} \langle t \rangle = \frac{c}{2} (t_0 + \Delta t I_{r^{-1}} \sum_i i * I_i)
\]

Then 3D reconstruction of the scene can be achieved based on the equation (5).

4. Validation via Simulation

To validate the proposed 3D image formation model, we performed simulations based on four gated viewing images from[16], which are shown in Figures 3. During the simulations, the size of images was chosen to be 256×256(hence, N=65536). Using \( M=16384 \) and \( 32768 \) pseudorandom projections \( \left( \frac{N}{4} \right) \) and \( \left( \frac{N}{2} \right) \), respectively, we reconstructed the 2D images using YALL1 shown in Figures 5(i) and Figures 6(i) as well as the 3D views shown in Figures 5(ii) and Figures 6(ii). In contrast, the original
reconstruction was shown in Figures 4. From these results, it was clear that the recognizable features of the Tank can be recovered. The reconstruction quality was also better as the higher M, according to the PSNR of the reconstructed 2D images using YALL1. However, it was not clear to find the slight range difference among these three 3D reconstructions.

Figure 3. Images of a scene captured using four different settings of the gate delay time, resulting in the laser reflections from the front (a), entire (b), back (c), and background (d) of the tank being imaged. The range to the target is 0.9 km and the gate width is 40 ns \cite{16}.

Figure 4. (i) 256×256 size chosen of Figure 3 (a), (b), (c), (d), respectively; (ii) Three-dimensional view of Tank reconstructed from the original gated image sequence simulated by Matlab.
Figure 5. (i) Wherein (a), (b), (c), (d) represent the CS-reconstructed gated image (PSNR=40.72dB, 37.59dB, 36.73dB, 34.95dB), respectively; (ii) Three-dimensional view of Tank reconstructed from the CS-reconstructed gated image sequence based on 16384 measurements equal to $\frac{N}{4}$ simulated by Matlab.

Figure 6. (i) Wherein (a), (b), (c), (d) represent CS-reconstructed gated image (PSNR=45.94dB, 42.91dB, 44.46dB, 40.94dB), respectively; (ii) Three-dimensional view of Tank reconstructed from the CS-reconstructed gated image sequence based on 32768 measurements equal to $\frac{N}{2}$ simulated by Matlab.
So, to evaluate the range differences between the original 3D reconstruction and the 3D reconstruction based on the proposed 3D image formation model of the scene with the tank, Lissajous figures were utilized. As known from Lissajous figures [17], if no optical path difference, equaling to no range difference, appears in the signals, one observes a single straight line; while with an increasing optical path difference, the loop of the Lissajous figure opens and widens. Therefore, in terms of small optical path differences, the data representation in a Lissajous-type eye pattern is very sensitive. Then from

**Figure 7.** Eye pattern Lissajous figure (M = 16384).

**Figure 8.** Eye pattern Lissajous figure (M = 32768)
the Figure 7 and Figure 8, the eye patterns was similar to a single straight line, reflecting that the range difference between original and reconstructed ones was not marked, but the eye pattern based on using M=16384 pseudorandom projections opened wider than that based on using M=32768 pseudorandom projections, which meant that the range accuracy was better as the increase of pseudorandom projections.

5. Conclusions
In this paper, through numerical experiments, we successfully applied YALL1 algorithm to estimate 2D measurements and generate 3D reconstruction of the scene with the tank by 3D image formation model based on the proposed prototype (a single-pixel gated viewing 3D imaging LADAR system). To minimize noise, the synchronous control mechanism in the prototype has been proposed. And the Lissajous figures based on Lissajous-type eye-pattern method was utilized with the aim of analyzing 3D reconstructions from different pseudorandom projections, which is an enhanced analysis in the means of range differences. However, the proposed system is limited due to the capabilities of the DMD arrays. The current DMD arrays can change their geometric configuration approximately 10K to 40K times per second [18]. For some applications, the system must keep the characteristic of high real-time at the expense of resolution, even at a rate of 40K times per second. To beyond the simulations, in terms of a single-pixel gated viewing 3D imaging LADAR system, building a physically realizable hardware optical scheme for practical application will be investigated in a future work.

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