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Time-of-flight range imaging using group testing

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ABSTRACT

In a low-light-level imaging system where photon radiation is quite sparse, the traditional Nyquist sampling may always cause a lot of excessive information, resulting in substantial increased cost and reduced speed. This paper introduces a group testing method to the photon detection field and builds a photon counting 3D imaging system. Our design relies on the interconnection of the binary matrices, contributing to the reduction of the photo multiplier tubes (PMT) and the excessive information, as well as the improvement of the system robustness. Besides, various binary interconnect matrices are designed to generate a threshold to improve the success rate of reconstruction. Analysis of the cross-talk of the fiber array and comparison of the group testing and compressed sensing are made further. Finally, our simulations show that images with large pixels can be successfully obtained by utilizing only a small number of PMT, due to the temporal and spatial sparsity of low level light.

1. Introduction

Photon counting 3D imaging [1] is a key detection technique in the low-level light field by acquiring 3D data cube of photon events to retrieve the space information of targets. It is mainly applied in single photon emission computed tomography, LIDAR, fluorescence detection, etc. [2], and is currently attracting substantial research interests because of its high potentials in medical diagnosis and military applications. So far, photon counting imaging technology has three major implementation methods. (1) Acquiring images via the scanning of targets with a single photon detector or a small photon detector array. This method is widely used and can achieve high-resolution images, but the mechanical scanning structure leads to a low imaging speed, low robustness and large volume [3]. (2) Single-pixel photon counting imaging based on compressed sensing. It can effectively reduce the number of photoelectric detectors, but DMD and other spatial light modulator may cause high loss of photons, which severely restrict the development [4]. (3) Single photon imaging with Wedge anode and MCP. This method can obtain high-resolution images without scanning, but each frame can only detect one photon [5].

Because of these drawbacks in the existing technologies, we here present a photon counting 3D imaging method based on group testing. In this work, various binary interconnect matrices are designed with proposed threshold to improve the success rate of reconstruction; the optical fiber array cross-talk is analyzed while the group testing and compressed sensing

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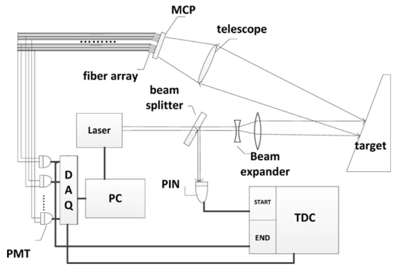

Fig. 1. Principle of the photon counting 3D imaging based on group testing.

are compared. In the end, the simulations are presented along with experimental results to reach the conclusions, thus providing directions for further research.

2. Group testing

Group testing [6] detects a subset of samples rather than a single sample, to achieve rapid detection of positive samples in large numbers of unknown samples. Group testing includes adaptive tests and non-adaptive tests. Because the non-adaptive tests is not dependent on the result of last test, it has a broader range of applications. The parameters of a non-adaptive test include the number of samples N, the number of positive samples k and the number of tests $T(N, k)$. In group testing, the k-disjunct matrix is defined as binary interconnect matrices which can determine no more than k positive samples. In binary matrix, if $m+1$ columns $\{c_0, c_1, \ldots c_m\}$ satisfy the condition that$c_0 \leq c_1 \cup c_2 \cup \cdots \cup c_m$, the column c_0 is covered by another m columns $\{c_1, c_2, \ldots c_m\}$. If any $k+1$ columns in matrix A cannot be covered by another k columns, the matrix A is a k-disjunct matrix.

The decoding of group testing is to judge whether the output y can cover the column of the matrix A. If the column a_j in A can be covered by the output y, the position of the column corresponding to the original signal f is 1, and vice zero. Summarizing, we have

$$f_j = \begin{cases} 1 & y \cup a_j = y \\ 0 & else \end{cases} \quad (1)$$

Where f is the original signal, a_j is the jth column of the matrix A, and y is the output signal, respectively.

3. 3D imaging model

The experimental model, as shown in Fig. 1, consists of a laser, a beam splitter and expander, a telescope, a micro-channel plate (MCP), a fiber array, and a time-digital converter (TDC). The laser light amplified by the beam expander hits the target surface, and then the reflected light collected by the telescope and the MCP goes into a fiber array connected with PMTs and TDCs for data acquisition. TDC is mainly used for the time of flight (TOF) ranging. When the signal is detected, the time can be recorded in the buffer. According to time difference between transmitting signal and receiving signal, one can calculate the depth.

$$D = \frac{ct}{2} \quad (2)$$

According to semi-classical optics statistical knowledge, in the low-light-level system, the light field satisfy Poisson random distribution. The probability of the presence of n photons in the average number of photons $\bar{n}$ is

$$p(\bar{n}, n) = \frac{(\bar{n})^n}{n!} \exp(-\bar{n}) \quad (3)$$

Thus, photons arrive at fiber pixel independently so that fiber pixel can be read as positive events at the fiber array made of $\sqrt{N} \times \sqrt{N}$ fiber optic splitters. Considering the light in the environment is low and the loss of splitter is serious, we need to enhance the energy of photons. Hence, a MCP and a fluorescent screen are adopted in this system.

4. Matrix design

There are three common methods to create k-disjunct matrix: Eppstein algorithm based on the Chinese Remainder Theorem [7], Macula algorithms based on containment relationship [8] and D'yachkov algorithm based on q-ary RS code [9].