Point target imaging simulation and experiment based on Temporal–Spatial Oversampling system

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Abstract: Temporal–spatial Oversampling (TSO) system has unique advantage for infrared point target detection. Infrared point target imaging simulations and experiments were designed. The shapes and energy distribution of point target in infrared image which were taken by TSO and ordinary sampling systems were researched. The point target imaging features were verified by the simulations and experiment results. First, principle of TSO system for point target imaging was compared with principle of ordinary sampling system, the main difference of the two sampling system was the arrangement of infrared detector's pixels. The arrangement of pixels in TSO system used half–sensor–alignment to improve the efficiency of point target energy collection. Then, imaging models of TSO and ordinary sampling system were built for simulations of point target imaging by two systems. The two systems characteristics were researched by simulations. And also the statistical characteristics of maximum pixels were analyzed. Simulation results show TSO system can get more stable point target imaging. Finally, infrared point target imaging experiments of two system were designed. The experiment results show that the temporal–spatial oversampling system can overcome the bad influence by phase noise. And the target images also have special characteristics in temporal–spatial oversampling system. These characteristics can make the infrared point target detection more effectively.

Key words: Temporal–Spatial Oversampling; infrared point target detection; scanning imaging

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时–空过采样系统对点目标成像仿真与验证

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摘 要: 为了验证时–空过采样系统对点目标探测的优越性，设计了红外点目标成像仿真及实验系统,研究并验证了时–空过采样获得的点目标图像形状、能量分布特点。首先,对比分析了时–空过采样系统与常规采样系统对点目标扫描成像原理;然后,对时–空过采样系统成像过程建立模型,通过仿真研究该系统对点目标的成像特点;最后,设计红外点目标成像实验并对实验数据进行分析。仿真及实验结果证明了时–空过采样克服了单采样对点目标成像能量分散的问题,图像信噪比至少提高 2 倍以上,且验证了经时–空过采样后,点目标像素之间具有特定的相关规律。利用时–空过采样的点目标成像特点,可为点目标的快速检出提供有利条件。

关键词: 时–空过采样; 红外点目标探测; 扫描成像

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1 Introduction

Temporal–Spatial Oversampling (TSO) system is usually used on space–based infrared scanning cameras to detect the targets which have very high temperature. The cameras always stay more than thousand miles away from targets, so the targets are little points to space cameras [1]. And energy of target will become weaken after passing through the long distance transmission. Point target movement will be very slow or even stationary to space infrared camera. Also because of long distance, it will cost a long time to calculate the target flight path. If the target is a missile, we hope that the target detection time shorter is better. It is hoped that target will be detected by single or few frames by infrared camera.

Point target energy will be collected by camera's optical system. Energy is focused on the camera focal plane. It will form a small image spot because of the Point Spread Function (PSF) effect. The size of image spot will be designed as same as size of infrared detector sensor in ordinary sampling system. The spot size is the minimum scale that camera can identify. Infrared point target detection camera in space usually use scanning camera. In ordinary sampling system, detector pixels are independent, and there is no overlap between the covers of each pixel scene. Because the image spot size is as same as the detector pixel size and spot position on focal plane is random, it is impossible that the whole energy of point target is collected by one detector pixel in ordinary sampling system in one frame. And the energy distribution on pixels that collect the target has no rule to follow. There is only one single pixel that can be used when we detect point target in one frame infrared image. The pixel has the highest value in target pixels those pixels collect one target energy. The energy distribution cause a decline of the signal to clutter rate which is very important in point target detection system. Target will become flashing in several consecutive images. The detection time will be correspondingly lengthened. And it is difficult to distinguish target from high frequency noise. Some scholars call the phenomenon as phase noise.

In order to solve the problem that caused by phase noise, TSO system is employed in infrared point target detection. SPIRIT III which is carried by Midcourse Space Experiment satellite is the first infrared instrument that used TSO system. The infrared detector pixels in TSO system have a special alignment which is main difference from ordinary sampling system. TSO system has same optical angular resolution as ordinary system. But the footprint on the ground that the detector pixel covered in TSO system is four times as that in ordinary system. There is overlap between coverage areas of adjacent pixels. In scanning direction, it will take two steps to scan over one pixel scene [2–3]. By temporal–spatial oversampling, point target energy will be fully collected by one pixel of detector. Besides the target pixels those collect target energy in one frame infrared image follow a certain rules, such as the middle pixel collect the full target energy. Those characteristic make point target detection become fast and accurate. Take advantage of these features, we can further process infrared image. Target strength is improved and suppression of clutter can be better[4–5].

To verify the advantages of TSO systems, TSO and ordinary sampling processes need to be modeled. Through the simulation of point target imaging in two sampling system. Point target energy distribution in infrared image should be well understood. Experiments are also necessary to compare the point target imaging effect by two sampling system.

2 Imaging characters of TSO

2.1 Imaging process of TSO

Angle resolution of a scanning camera is the angle which scanning mirror scans in an integral time of detector. Size of a target opens a very small angle to the camera. This angle is often smaller than angle resolution as Fig.1 shows.

The length that corresponds with angle resolution is denoted by d in Fig.1. It is also called scanning step as scanning image moves d on focal plane in an integral time.

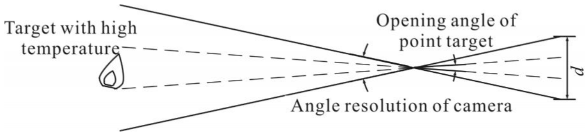
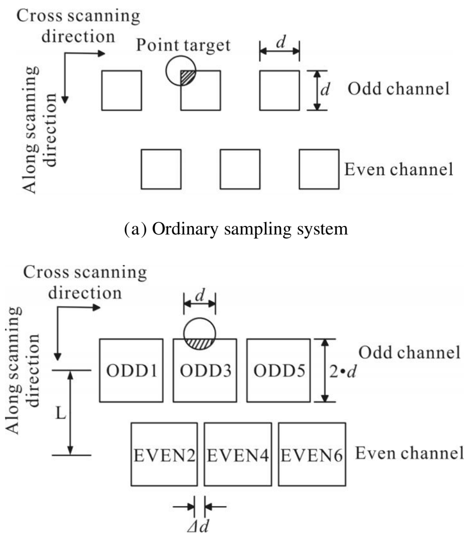


Fig.1 Target angle and camera's angular resolution

Because of PSF, a point target become a blurred facula on focal plane[6-7]. The blurred facula energy distribution fitts Gaussian distribution. In TSO system, optic mirrors should be designed to make sure that diameter of the blurred facula is equal to d. And the detector pixel size should be equal to $2 \cdot d$. If the same optics system is employed in an ordinary sampling system, detector pixel size should be d to match angle resolution. The alignments of detector pixels in two sampling systems are showed in Fig.2.



(b) Temporal spatial sampling system

Fig.2 Alignment of detector pixels

Affected by the manufacturing process, pixels of scanning infrared detector are divided into two channels, odd channel and even channel. Pixels of odd channel generate the odd columns of image picture, and even channel pixels generate the even ones. The two channels don't exposure the target at the same time. So the data of the two channels should be corrected to eliminate the influence of channels imaging time difference.

In ordinary sampling systems, it is rarely happened that energy of the blurred facula is sampled by one detector pixel, because target could be anywhere on focal plane. Most of time, the energy dispersed on several pixels, and Signal to Noise Rate (SNR) would be decreased. It is called Phase Noise[8] in some articles. In TSO system, the size of detector pixels is as twice as blurred facula, so when target is scanned through the pixel, the target will be sampled three times by single pixel in most cases as Fig.3 shows. As Fig.2(b) shows, EVEN2 and ODD3 have almost 50% overlap, so do EVEN4 and ODD3. Point target will be sampled by these three pixels, and the energy sum of EVEN2 and EVEN4 is equal to ODD3. But odd channel and even channel don't sample the target at the same time. So correctness should be done, to eliminate the time difference [9]. After correctness, target image should be arranged like Fig.3 shows. The sizes of shadows indicate how much energy is sampled by pixel.

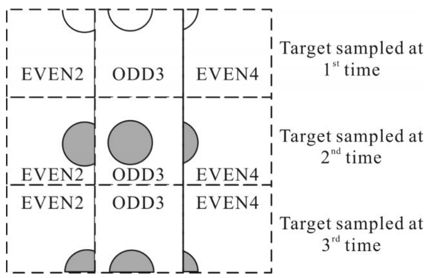


Fig.3 Point target's energy collection of TSO system

2.2 Simulation of sampling processes

In ordinary and TSO system, various positions of point target make different energy sampled by detector pixels. Image of target could also be different. To analyze how severe the difference influents point target detection, virtual models of the two sampling systems are built.

An image with high resolution is used as background which will be sampled. Slide integration is employed to simulate the process of scanning imaging, and it is assumed that scanning image moves N background image pixels (BIPs) in an integration time along scanning direction. According to the relationship between scanning step and detector size, detector field of view (FOV) covers $N \times N$ BIPs in ordinary sampling system, while $2N \times 2N$ BIPs in TSO system.

When imaging process of ordinary sampling is simulated, sliding window is set as $N\times N$ BIPs in background image corresponding to FOV of a detector pixel. The sum of BIPs value in single window is represented as p_k, k means that the window has slidden k times. It is needed to slide N times to finish the simulation of scanning imaging in one integration time. The imaging value of a detector pixel in ordinary sampling system is generated as followed function shows.

$$P(t)=\sum_{k=1}^{N} p_k(t) \tag{1}$$

After one integration time, the detector pixels which are aligned across scanning direction generate one line of sampled image. The FOVs of detector pixels do not overlap in ordinary sampling system. Several lines constitute a whole image. The integration sliding process of TSO system is similar with ordinary sampling system, except that sliding window has $2N\times 2N$ BIPs. Also, there are N BIPs overlap between odd pixel′s FOV and even pixel′s.

It is a good method to use Gaussian model to simulate PSF[10], the model expression is:

$$z(x,y)=\frac{1}{2\pi\sigma^2}\exp\left(-\frac{(x-x_0)^2+(y-y_0)^2}{2\sigma^2}\right) \tag{2}$$

(x_0,y_0) is center position of target. σ is standard deviation of Gaussian function and it should be designed to make 80% energy of target to be sampled in angle resolution, $N\times N$ BIPs equivalently.

To make the simulation to be ergodic, the point target is put in background image in order as Fig.4 shows, M is a positive integer which is much larger than N.

Image of point targets before and after sampling simulation are showed in Fig.5.

The values of point target after once simulation by two sampling simulation are:

$$\begin{bmatrix} 0.114, 0.335 \\ 0.135, 0.399 \end{bmatrix}, \begin{bmatrix} 0.115, 0.453, 0.340 \\ 0.249, 0.983, 0.738 \\ 0.138, 0.543, 0.407 \end{bmatrix}$$

According to the result of simulation, it is easy to find out that point target has distinct features in TSO image which don′t appear in ordinary sampled system. First, a point target which corresponds to the angle resolution turns into 3×3 pixels after sampled. Second, the center of the 3×3 pixels collected almost total energy of point target. Last, in each line of 3×3 pixels, sum of 1st pixel value and the 3rd pixel value is equivalent to the 2nd pixel value approximately. While the point target in ordinary sampled image turns into 2×2 pixels, and each pixel only get a part of target energy. The values of target pixels are totally random.

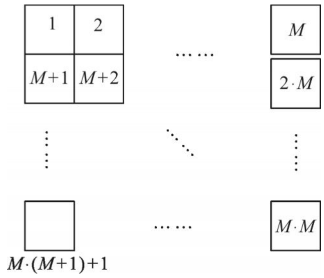


Fig.4 Position sequence of point targets in background

(a) Point target in background (b) Point target sampled by ordinary sampling (c) Point target sampled by TSO

Fig.5 Point target image before and after sampling

Specially, the statistical characteristics of maximum value of pixels in two sampling system is showed in Fig.6.

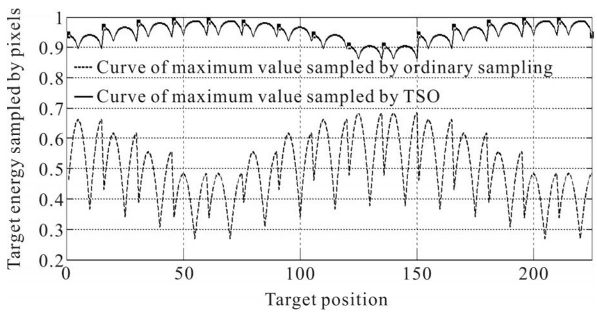


Fig.6 Comparison of maximum target pixel value in two sampling systems

The maximum value of target pixels in ordinary sampling system is 67% of total target energy, but in TSO system this data is 99%. The stand deviation of maximum value of target pixels is 0.1 in ordinary sampling system, but in oversampled system it is 0.03. It means point target sampled by TSO system has more stable characters than sampled by ordinary sampling system.

3 Contrast experiments

To test and verify the correctness of simulation, contrast experiments are designed. The instruments used in experiments as showed in Fig.7 are same except infrared detectors.

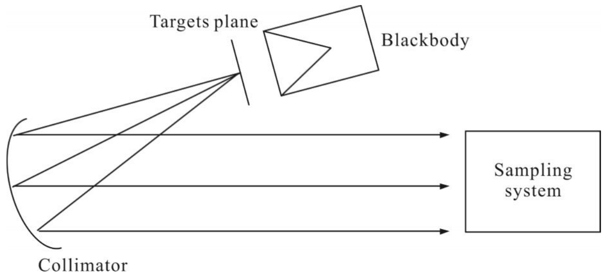


Fig.7 Schematic diagram of experiment

The purpose is to compare the target imaging sampled by two systems, and background should be restrained. So detection of spectrum is set between 2.7–2.95 μm which is the atmospheric absorption spectrum in order to reduce the impact of background. All of nine targets temperature are 350 ℃, and IR images by two sampling systems are showed in Fig.8.

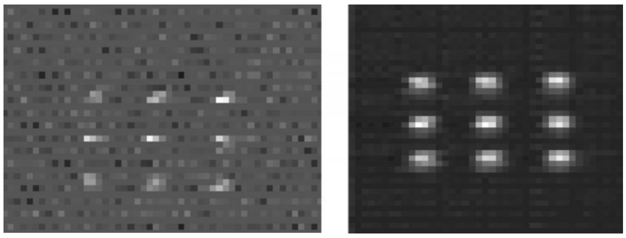


Fig.8 Infrared point targets images sampled by different systems

In ordinary sampling image, the targets pixels are little bit lighten to background, and the shapes of targets are not stable. But in oversampling image, the targets pixels are much lighten to background, and have stable shapes. In IR point targets detection system, the signal to clutter rate (SCR) is very important, the target would be more easy detected with high SCR. In the experiments, SCR is defined as:

$$SCR=\frac{T_{\max}}{B}$$

$T_{\max}$ is the maximum pixel value of each target, B is the background value. A window which is composed by 13×13 non-target pixels is used to estimate background value. The SCRs of images sampled by two systems are shown in Fig.9.

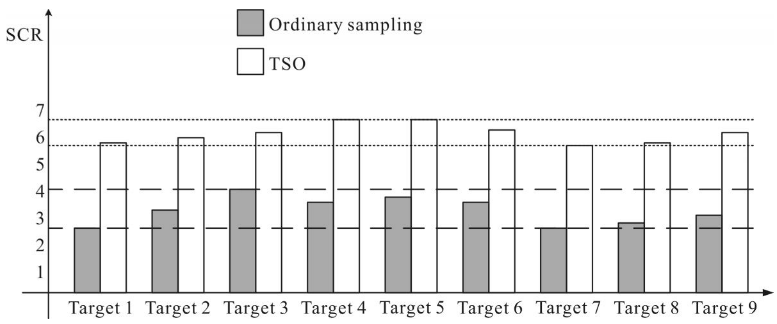


Fig.9 SCRs of images sampled by two systems

It is can be seen the image sampled by TSO has more stable and higher SCR (almost twice times) than the image sampled by ordinary sampling system. Besides, the TSO targets have more stable shape and certain pixel value regulation. The nine TSO targets pixels value are showed below:

$$\begin{bmatrix} 0.094 & 0.659 & 0.348 \\ 0.153 & 0.802 & 0.701 \\ 0.169 & 0.701 & 0.719 \end{bmatrix} \begin{bmatrix} 0.152 & 0.758 & 0.440 \\ 0.263 & 0.835 & 0.666 \\ 0.224 & 0.744 & 0.619 \end{bmatrix}$$

$$\begin{bmatrix} 0.368 & 0.857 & 0.481 \\ 0.419 & 0.904 & 0.556 \\ 0.298 & 0.626 & 0.417 \end{bmatrix} \begin{bmatrix} 0.226 & 0.671 & 0.121 \\ 0.614 & 0.94 & 0.212 \\ 0.684 & 0.854 & 0.236 \end{bmatrix}$$

$$\begin{bmatrix} 0.416 & 0.736 & 0.12 \\ 0.694 & 0.944 & 0.211 \\ 0.715 & 0.859 & 0.192 \end{bmatrix} \begin{bmatrix} 0.586 & 0.755 & 0.122 \\ 0.707 & 0.880 & 0.189 \\ 0.608 & 0.709 & 0.134 \end{bmatrix}$$

$$\begin{bmatrix} 0.094 & 0.464 & 0.195 \\ 0.369 & 0.793 & 0.426 \\ 0.424 & 0.767 & 0.513 \end{bmatrix} \begin{bmatrix} 0.231 & 0.575 & 0.226 \\ 0.529 & 0.826 & 0.376 \\ 0.551 & 0.806 & 0.396 \end{bmatrix}$$

$$\begin{bmatrix} 0.479 & 0.741 & 0.282 \\ 0.636 & 0.888 & 0.358 \\ 0.566 & 0.774 & 0.329 \end{bmatrix}$$

It is obvious that the center of the 3×3 pixels has the max value, this value is very stable too. And in each line, sum of 1st pixel value and the 3rd pixel value is equivalent to the 2nd pixel value approximately. The correctness of simulation is verified.

4 Conclusions

According to the result of simulation and experiments, it is obvious that TSO system can take a better infrared point target image than ordinary sampling system. Because of special alignment of detector pixel, almost full energy of point target can be collected by one pixel. Results of simulation also show the maximum pixel collect 99% energy of point target. But this value is 67% in ordinary sampling system. Statistical results show maximum pixel is more stable in TSO system than in ordinary sampling system. That means target will not be flashing in TSO images. Pixels around full-energy pixel in TSO images also collect some part of target energy. The energy distribution in those pixels follows a certain rules, such as sum of both sides pixel value is equal to the middle pixel value along across scanning direction. This is the unique feature of point target image taken by TSO. It can be easy to distinguish between target and clutter after using match -filter to strengthen the target. Experiment result shows that SCR in TSO image will be almost twice times as ordinary sampling system under the same imaging conditions. Besides, point targets have certain shapes in TSO image. Meanwhile shapes of target are random in ordinary sampling image. Due to the TSO imaging features, infrared point target can be easily and fast detected.

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