Research on Processing Methods for Laser Ranging Images Acquired by CMOS Cameras (Postprint)

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Abstract

The application of CMOS cameras to the laser ranging system of the 53 cm binocular telescope at Yunnan Observatory has substantially enhanced the ranging echo detection rate and success rate for space targets. Building upon the analysis of digital image data acquired by the CMOS camera, an optimized image processing and laser spot extraction algorithm is proposed, which effectively realizes laser spot identification and extraction of target centroid coordinates. The procedure first employs median and mean filtering for image denoising, subsequently utilizes Otsu' s method for threshold calculation and image binarization, and selects the Roberts operator for edge extraction. Finally, the least squares method is applied for linear fitting to determine the spot coordinates and compute their positional deviation. These results carry significant implications for further investigation into the application of CMOS cameras within the 53 cm binocular telescope laser ranging system.

Full Text

Research on Laser Ranging Image Processing Methods for CMOS Camera Acquisition

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Abstract: The application of CMOS cameras to the 53 cm binocular laser ranging system at Yunnan Observatory has significantly improved the echo rate and success rate of space target ranging. Based on the analysis of digital image information acquired by CMOS cameras, we propose an optimized image processing and laser spot extraction algorithm that effectively achieves laser spot recognition and target centroid coordinate extraction. The method first employs median filtering and mean filtering for image denoising, then uses the Otsu method to calculate thresholds for image binarization, and selects the Roberts operator for edge extraction. Finally, least squares fitting is applied to solve for the spot coordinates and calculate their position deviation. These results are important for further research on the application of CMOS cameras in the 53 cm binocular telescope laser ranging system.

Keywords: laser ranging; image segmentation; edge detection; linear fitting; laser spot recognition

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Since 1998, Yunnan Observatory has been conducting laser ranging work and has accumulated rich experience. In 2009, the observatory began regular kHz satellite laser ranging observations and space debris laser ranging experiments, with continuously increasing numbers of observed passes and effective data points, playing an important role in the international laser ranging network [1]. In 2016, a new 53 cm binocular telescope laser ranging system was constructed, featuring a split-beam ranging configuration where one tube emits laser pulses and the other receives echo signals reflected from space targets. The system officially joined the international laser ranging network in 2017 with the station code 7819. In addition to regular laser ranging operations, this system can also be used for space debris laser ranging experiments.

During laser ranging, the telescope tracks targets based on satellite orbit predictions. For visible targets, monitoring is performed through a camera in the receiving optical path. Satellite prediction refers to generating an observable satellite list based on satellite ephemeris data for targets passing over the station, helping observers plan observation schedules reasonably. Based on the corresponding satellite ephemeris data, the predicted positions in azimuth and elevation for planned observation targets are calculated, which serve as telescope tracking guidance data [2]. Due to deviations between predicted and actual orbital positions of space targets (especially space debris), observed targets often deviate from the center of the camera' s field of view. Therefore, for visible targets, the 53 cm binocular telescope control system employs television closed-loop tracking to lock the target at the center of the receiving camera' s field of view. In 2015, the tracking camera was upgraded from a video CCD to a CMOS camera. With the CMOS camera, fainter targets can be observed, enhancing the system' s capability to detect dim targets and making identification of targets and laser spots feasible.

When laser pulses are emitted through the atmosphere, various physical processes occur through interactions with atmospheric molecules and aerosol particles, including Rayleigh scattering by molecules and Mie scattering by aerosol particles, which generate backscattered light. This backscattered light directly represents the emission direction of the laser [3]. Consequently, during laser ranging, backscattered light enters the CMOS camera, and the laser backscattering background noise signal directly affects target recognition and miss distance extraction—this is a common issue in split-beam laser ranging systems. Changchun Observatory has applied image processing methods to identify target centroids and laser spots to address this problem, with reference [1] providing effective target recognition and spot extraction methods. Investigations reveal that [1, 4-5] represent partial solutions to related problems: reference [4] applies mean filtering for daytime ranging image preprocessing and vector boundary scanning to detect beam edge information, while reference [5] proposes an image accumulation denoising method. However, due to the wedge-shaped beam splitter in the 53 cm binocular telescope' s receiving optical path, which has reflections from both front and rear surfaces that cannot focus together, two images are formed on the CMOS camera. The captured images show two beams and two targets, making the methods in the aforementioned literature unable to identify the spots. Therefore, new spot identification methods must be developed for this system.

This paper investigates effective methods for identifying targets and laser spots under strong background noise, specifically addressing the characteristics of the 53 cm telescope ranging system' s receiving optical path. The results can be applied to telescope target tracking closed-loop control, laser emission direction correction, laser echo signal searching, and analysis of target characteristics such as brightness and rotation period.

1.1 Laser Ranging Images

[Figure 1: see original paper] shows the optical path diagram of the 53 cm binocular telescope laser ranging system [6]. During ranging and tracking of space targets, the C-SPAD detector receives target echo signals while the CMOS camera tracks and monitors visible ranging targets. The specific parameters of the telescope' s CMOS camera receiving system are listed in Table 1 . For example, the camera field of view is 0.5°, and the pixel size is 6.5 m × 6.5 m. As mentioned above, due to deviations in space target orbit predictions, images captured by the CMOS camera when tracking targets according to orbit predictions often show that the camera field center, target, and laser spot do not coincide, as illustrated in Figure 2 [Figure 2: see original paper]. To obtain echo signals, both the target and laser spot must be adjusted to the center of the CMOS camera' s field of view, as shown in Figure 3 [Figure 3: see original paper]. The captured images clearly show two beams; if the target is relatively bright, two targets can also be observed simultaneously.

Table 1 Parameters of the telescope receiving system

Parameter	Value
Telescope aperture	530 mm
Camera effective pixels	2048(H) × 2048(V)
Camera pixel size	6.5 m × 6.5 m
Camera exposure time	10 s–10 s

Addressing the characteristics of images acquired by the CMOS camera, this paper first filters the collected image data to remove noise, then separates targets and beams through thresholding. After separation, target centroid coordinates are extracted on one hand, and on the other hand, morphological opening and closing operations are performed on the binary image to detect beam edges. Least squares linear fitting is applied to the edge data to obtain spot coordinates. Since the 53 cm binocular telescope has been conducting regular international laser ranging operations, this research on CMOS data image processing methods for the 53 cm binocular telescope is conducted using digital image data from laser ranging satellites.

1.2 Image Preprocessing

Figure 4 [Figure 4: see original paper] shows a digital image of the laser ranging satellite Lageos1, with an orbital altitude of 5850 km and a camera exposure time of 500 ms. The image shows two beams and two targets. Due to the lower reflectivity of the rear surface, the reflected light is weaker, resulting in a fainter target and beam visible in the image. Image preprocessing for laser ranging images refers to filtering for noise removal and binarization.

Various filtering methods including median filtering, Gaussian filtering, mean filtering, and negative transformation were applied to numerous collected laser ranging images for denoising. Through comparative analysis of the results, this paper adopts median filtering and mean filtering. Since image noise originates primarily from two sources—system noise and sky background noise—mean filtering and median filtering are used for image preprocessing. The results are shown in Figure 5 [Figure 5: see original paper], with a 5 × 5 filter window for mean filtering and a 3 × 3 filter window for median filtering. The corresponding contour plots are shown in Figures 6 [Figure 6: see original paper] and 7 [Figure 7: see original paper]. The contour plots demonstrate that both filtering methods provide effective preprocessing, removing noise around targets and beams while preserving complete edges.

Since two beams are present, edge determination at their connection becomes difficult during binarization, affecting beam extraction. The two beams differ significantly in pixel intensity and can be separated through thresholding. Threshold segmentation is a typical image segmentation algorithm, with common methods including histogram bimodal method, maximum entropy method, Otsu method, and gradient statistics method [7]. Among these, the Otsu method is widely applied due to its good segmentation effect and broad applicability. Also known as the maximum between-class variance method or minimum within-class variance method, this method is based on the image' s gray-level histogram and uses the criterion of maximizing between-class variance or minimizing within-class variance between target and background for threshold selection [8], achieving good segmentation results in many cases.

This paper employs the Otsu method for threshold segmentation, with results shown in Figures 8 [Figure 8: see original paper] and 9 [Figure 9: see original paper]. This method works well for most targets, though segmentation of faint targets remains challenging. Holes appear in the middle of binary images because the 53 cm binocular telescope is a central coaxial reflective telescope, and the receiving secondary mirror causes central obstruction, resulting in smaller central pixels for the laser beam in the image.

1.3 Target Recognition and Centroid Coordinate Calculation

Satellite targets appear as approximately circular spots. In binary images, satellite target pixels are relatively concentrated, with target length and width being approximately equal [5]. During binarization, targets and beams can be separated due to their significant pixel intensity differences. Connected regions in the image are searched as target regions, and traditional centroid algorithms are used to calculate target centroids [9]. The calculation process is:

$$x_c = \frac{\sum_i \sum_j x_i G(x_i, y_j)}{\sum_i \sum_j G(x_i, y_j)}, \quad y_c = \frac{\sum_i \sum_j y_i G(x_i, y_j)}{\sum_i \sum_j G(x_i, y_j)}$$

where (x_c, y_c) represents the target centroid coordinates; (x_i, y_j) are the image coordinates of each pixel; and $G(x_i, y_j)$ is the gray value. Essentially, the moment of the star point' s gray value is calculated relative to area, then area averaging is performed within the region to obtain centroid coordinates, denoted as $p_0(x_0, y_0)$. The results are shown in Figure 10 [Figure 10: see original paper].

1.4 Laser Spot Recognition and Spot Coordinate Calculation

Laser spot recognition is based on edge detection and line fitting to find intersection points on binary images. Edges are the most fundamental features of images and contain most of the image information. Edge detection essentially employs algorithms to extract boundary lines between objects and background in images. Only through edge detection and extraction can targets be distinguished from background [10]. Common methods include differential edge detection, Roberts edge detection operator, Sobel edge detection operator, Prewitt edge detection operator, Laplace edge detection operator, and Canny operator. These operators utilize first derivative maxima, second derivative zero-crossings, or appropriate threshold selection to obtain image edges, but all have certain limitations [11].

Some have poor noise suppression capability, while others poorly maintain edge connectivity.

The Roberts operator uses the approximate gradient magnitude of differences between diagonally adjacent pixels to detect edges. The operator provides relatively precise localization and consists of two 2 × 2 matrices, but is sensitive to noise as it does not include smoothing [12]. The convolution matrix of the Roberts operator is: [], with the specific formula: $g(x, y) = |f(x, y) - f(x + 1, y + 1)| + |f(x + 1, y) - f(x, y + 1)|$. Since images were already filtered during preprocessing, and after comparing processing results from numerous laser ranging images, the Roberts operator was selected, yielding the edge image shown in Figure 11 [Figure 11: see original paper].

Holes in the beam of binary images affect data extraction after edge detection. This paper employs hole-filling methods on binary images to eliminate these holes. In image processing, morphological structure elements are used to measure and extract corresponding shapes from images for analysis and recognition purposes. Mathematical morphology applications can simplify image data while preserving their basic shape characteristics and removing irrelevant structures [13].

The filtered binary image undergoes closing operation first, which eliminates narrow discontinuities and long, thin gaps, removes small holes, and fills breaks in contour lines [14]. This is followed by opening operation, which smoothes object contours, disconnects narrow discontinuities, and eliminates thin protrusions [15], effectively filling the middle portion of the beam (as shown in Figure 12 [Figure 12: see original paper]). Due to atmospheric scattering and reflection effects, laser images have certain deviations, particularly with larger data errors at the tip and tail of the laser beam [4], which cannot accurately reflect beam edge information. By finding the largest connected region and removing the beam tip and tail (as shown in Figure 13 [Figure 13: see original paper]), these points are excluded from line fitting after edge detection, yielding better laser beam edge information and improving spot positioning accuracy.

Traditional edge detection algorithms produce relatively thick edges with low positioning accuracy. Edge thinning can be achieved by applying non-maximum suppression and binarization to the gradient image after convolution. Non-maximum suppression compares the current pixel' s gradient value with two adjacent gradient values along its gradient direction. If smaller than adjacent gradient values, the pixel is considered a non-edge point; otherwise, it is an edge point [16]. If the gradient value exceeds the set threshold (100 in this paper) and the point is a local maximum, it is defined as an image edge point; otherwise, it is a non-edge point.

Edge detection using the Roberts operator on the binary image after opening and closing operations (as shown in Figure 14 [Figure 14: see original paper]) yields relatively accurate edge localization after non-maximum suppression (as shown in Figure 15 [Figure 15: see original paper]). Least squares fitting is applied to laser beam edge data, with the intersection of two fitted lines representing the spot, denoted as $p(x, y)$. The calculated laser spot coordinates are shown in Figure 16 [Figure 16: see original paper].

2 Results Analysis

On the nights of January 7, 23, 24 and February 26, 27, 2018, the 53 cm binocular telescope was used to observe laser ranging satellites and acquire images. Table 2 lists the laser ranging satellites from which images were acquired. These images were captured when echo signals were present, meaning the laser spot was aligned with the target. Figure 17 [Figure 17: see original paper] shows the spot fitting results and filled images superimposed for the Hy2a and Jason2 satellites after image processing, demonstrating that the fitted spot positions align with the targets. Processing images of Glonass102 with different exposure times yielded good results for all 13 images. The differences between spot coordinates and target centroids for different exposure times (300 ms, 500 ms, 800 ms) are shown in Figure 18 [Figure 18: see original paper].

Processing ranging images through this series of algorithms effectively identifies target centroids and laser spot positions. As shown in Figure 17, the method achieves good results. A total of 91 images with echo signals were processed, and differences between spot coordinates and centroid coordinates were calculated. Data for different targets and exposure times are shown in Figure 19 [Figure 19: see original paper], where the horizontal axis represents the number of processed target images and the vertical axes show deviations in x and y directions. The results demonstrate that deviations between spots and target centroids are relatively small with stable overall trends, indicating that this method effectively handles most practical situations and successfully identifies targets and spots.

Table 2 List of missions

Mission	Altitude	Exposure Time
SwarmB	460 km	500 ms
Cryosat2	720 km	100 ms
Saral	814 km	300 ms
Geoik2	943.5-973.5 km	500 ms
Beacon	972 km	300 ms
Ajisai	1485 km	500 ms
Jason2	1336 km	300 ms, 400 ms, 500 ms, 600 ms, 800 ms
Jason3	1336 km	300 ms, 400 ms, 500 ms, 600 ms, 800 ms
Lageos2	5625 km	400 ms, 600 ms, 800 ms
Lageos1	5850 km	500 ms
Glonass102	19140 km	300 ms, 500 ms, 800 ms
Galileo101	23220 km	800 ms

The 53 cm binocular laser ranging system at Yunnan Observatory employs a high-performance CMOS camera for target tracking, which has improved space target ranging echo rates and success rates. In laser ranging, strong laser backscattering causes both targets and laser beams to appear simultaneously in CMOS camera images. Because the beam splitter in the telescope' s receiving optical path is wedge-shaped with reflections from both front and rear surfaces that cannot focus together, two star images and two spots appear in the CMOS camera. Therefore, research on extracting target centroids and spot coordinates is crucial for effectively utilizing data acquired by CMOS cameras.

This paper incorporates morphological opening and closing operations into classical image processing methods for satellite laser ranging images, solving the problem of dual beams in image processing and achieving effective target recognition under strong laser backscattering background noise. Multiple experiments demonstrate good extraction results, though identification of faint targets remains problematic. Future work will focus on applying these recognition results to telescope television closed-loop tracking and analysis of other target characteristics.

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Note: Figure translations are in progress. See original paper for figures.