An approach of target photometric measuring for theodolite visible light imaging

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Abstract. Photoelectric theodolite is important optical measurement equipment in pelagic aerospace TT&C systems. The visible light imaging method helps capture significant information of the observed target, photometric information is one of them. To achieve expediently and quickly target photometric measuring, it studies and realizes a measuring method, by using stars in the same field of view as the observed target in this paper. Firstly, it calculates the gray values for target and star by image processing algorithm in the image captured by theodolite. Then magnitude information of the star is obtained by using a star catalogue. Lastly, magnitude of the target is calculated by antitheses method. The approach is implemented to investigate the measuring performance and an experiment is carried out by using images containing at least two stars. The result shows good performance of the proposed method.

1. Introduction
Pelagic aerospace survey ship is an important part of space TT&C system, and its ability of moving at sea makes up for the limited coverage of land TT&C station. The photoelectric theodolite is important optical measurement equipment on the ship. It realizes imaging and observation of measured target by optical means. Visible light imaging is a common imaging method of theodolite equipment [1, 2]. By analyzing its image, a lot of information about the target can be acquired, among which photometric information is an important one [3]. The attitude controlling state of the target can be calculated by observing the changing law of its photometric information, so as to determine whether the target works normally [4]. To achieve expediently and quickly target photometric measuring, a measuring method is proposed by using stars in the same field of view as the observed target.

2. Target photometric measuring method
At present, the methods of photoelectric measurement of target photometry mainly include photometry measurement and CCD measurement [5]. As the CCD measurement does not need special measurement hardware, the optical structure design of the system is simplified, and the complexity and cost are reduced. Therefore, the measurement method is the most widely used, and relevant scholars have conducted a lot of research [6]. The commonly used CCD measurement methods include aperture photometry, point spread function (PSF) fitting photometry, and methods combining the two measurements [7]. The above methods utilize complex image processing technique and parameter determination algorithms, which is very suitable for the scene with strong equipment...
detection ability, large observation field, large number of stars in the image and high measurement accuracy requirements [6, 8]. In view of the characteristics of small field of view and simple image content in the actual observation of photoelectric theodolite on survey ship, this paper presents a convenient and fast method of target photometry measurement.

The proposed approach adopts the principle of antitheses method. Firstly, image processing technique is used to obtain the image gray value of the target and the stars in the same field of view. Then, the theodolite azimuth-elevation information, the ship position and attitude information are used to calculate the direction of the theodolite in the celestial coordinate system. Further, magnitude of the star in the same field of view is obtained by querying the star catalogue. Finally, the relationship between the magnitude of different targets and their image gray levels is adopted to calculate the magnitude of observed target which is output as its photometric measurement information.

3. Target photometric measuring approach using stars in the same field of view

3.1. Gray value calculation of target and star in the image

In the local area of point target and star imaging, it can be seen as the superposition of the influence of background and target illuminance. As shown in Figure 1, the dark-colored area is the concentration area of target imaging, the light-colored area is the diffraction area during the imaging process and the white area is the background imaging area. As the energy of imaging in diffractive region also comes from imaged target, this part of gray value must be included in the total gray value of the target. However, the size of this region is related to the imaging energy and optical system, so it can not be calculated exactly [9]. In this paper, an approximate method is used to calculate the total gray value of the target (or star).

![Figure 1. Sketch of target imaging.](image)

The total gray value of the local area consists of two parts, one is the gray value of the imaged target (or star), the other is the gray value of background. Therefore, the total gray value of the target can be obtained by subtracting the background gray value from the local area. Assuming that the background energy is white noise with mean $E_B$, and the corresponding mean image gray value is $D_B$, then the total gray value of the imaged target is

$$D_T = \sum_{i=1}^{N} G_i - D_B N$$  \hspace{1cm} (1)

Where, $N$ is the amount of pixels in the local area, $G_i$ is the gray value of the $i$th pixel in the area. Therefore, how to calculate $D_B$ is the key of the problem.

The image processing method is used to segment the region. Firstly, the region is divided into two parts, light and dark, by the OTSU method [10] and the centroid is calculated used as the target imaging center $S_T$, represented by $(x_T, y_T)$. Then, the edge detection technology is adopted to get the segmentation boundary, the red circle in Fig.1. Finally, the open operation is used to expand the circle radius to a certain pixel, the yellow circle in Fig.1, so as to ensure that the diffraction area is all included in the circle region. Then, the area outside the yellow circle can be considered as background
area. The total number of pixels in the background area is \( N_B \) and the total gray value of the area is \( G_B \), then

\[
D_g = G_B / N_B \tag{2}
\]

3.2. Magnitude of the star in the same field of view

3.2.1. Spatial direction of the theodolite

By using the recorded data in the actual observation, the longitude \( L \), latitude \( B \), altitude \( H \), heading angle \( \kappa \), pitch angle \( \psi \) and roll angle \( \theta \) of the survey ship, as well as the azimuth angle \( A \) and elevation angle \( E \) of the theodolite, at a certain observation time \( t \) can be queried.

Firstly, \( A \) and \( E \) are modified by theodolite axis parameters.

\[
(A, E) = \text{AxisRec}(A, E, g, c, h, b, a, a_h)
\tag{3}
\]

Where, \( g \) is the orientation error, \( c \) is the collimation error, \( h \) is the zero error, \( b \) is the horizontal error, \( a \) is the vertical error, \( a_h \) is the inclined direction.

Then, according to the ship's attitude, the direction vector of the theodolite optical axis in the local horizontal coordinate system can be calculated.

\[
r_g = R_z(\kappa, \psi, \theta)R_x(\kappa, E_i)\cdot [1, 0, 0]^T
\tag{4}
\]

Where

\[
\begin{align*}
R_z(\kappa, E_i) &= R_z(A_i)R_z(-E_i) \\
R_x(\kappa, \psi, \theta) &= R_x(\kappa)R_x(-\psi)R_x(-\theta)
\end{align*}
\tag{5}
\]

Where, \( R_x(\cdot) \), \( R_y(\cdot) \) and \( R_z(\cdot) \) are cosine matrices rotating around the X, Y, and Z axes, respectively.

Finally, azimuth angle \( A_e \) and elevation angle \( E_e \) of the theodolite optical axis in the local horizontal coordinate system can be obtained as

\[
\begin{align*}
A_e &= \tan^{-1}\left(\frac{r_g(3)}{r_g(1)}\right) \\
E_e &= \sin^{-1}\left(\frac{r_g(2)}{r_g(1)}\right)
\end{align*}
\tag{6}
\]

According to the longitude and latitude information of the survey ship at moment \( t \), the cosine matrix \( R_x(L, B) \) from the local horizon coordinate system to the geocentric coordinate system can be obtained. Using the time information, the cosine matrix \( R_x(t, \xi) \) from the geocentric coordinate system to the celestial coordinate system can be calculated, where \( \xi \) is a set of parameters such as polar and nutation. With \( r_g \), it can be obtained that the direction vector of the theodolite optical axis in the celestial coordinate system is

\[
r_t = R_x(t, \xi)R_x(L, B)\cdot r_g
\tag{7}
\]

Furthermore, the right ascension \( L_g \) and declination \( B_g \) of the optical axis are

\[
\begin{align*}
L_g &= \tan^{-1}\left(\frac{r_t(3)}{r_t(1)}\right) \\
B_g &= \sin^{-1}\left(\frac{r_t(2)}{r_t(1)}\right)
\end{align*}
\tag{8}
3.2.2. Star magnitude determination with star catalogue

The Hipparcos catalogue is employed for preprocessing and used for subsequent star magnitude confirmation.

The purpose of catalogue preprocessing is to classify the stars, reduce the calculation of star recognition process, and improve the processing efficiency. During the processing, a 360 × 180 list array is constructed. According to its right ascension and declination, each star in the catalogue is added to the corresponding list in the array. If one star’s right ascension is \( \alpha \) and declination \( \delta \), then

\[
\begin{align*}
  r & = \text{round}(\alpha + 0.5) \\
  c & = \text{round}(\delta + 90.5)
\end{align*}
\]

The star is added to the list in \( r \) th row, \( c \) th column, where, \( \text{round}(\cdot) \) is rounding function.

To the theodolite optical axis

\[
\begin{align*}
  r & = \text{round}(\alpha + 0.5) \\
  c & = \text{round}(\delta + 90.5)
\end{align*}
\]

For all stars, represented by set \( \{S_i\} \), in lists in row from \( r - 1 \) to \( r + 1 \), column from \( c - 1 \) to \( c + 1 \) of the array, their pixel positions in the image can be calculated by projection with imaging model and parameters of the theodolite, which can be represented by \( (x_0, y_0) \), respectively. Due to the influence of atmospheric refraction in the actual imaging process, the impact needs to be considered in the stars projection. The modified projection position \( S_i \) is expressed as

\[
\begin{align*}
  x_i &= x_0 - 0.016722 \cot(E_0)/d_a \\
  y_i &= y_0 - 0.016722 \cot(E_0)/d_a
\end{align*}
\]

Where, \( E_0 \) is the elevation angle of the theodolite in the local horizontal coordinate system, and \( d_a \) is the angular resolution of the theodolite when imaging.

Then calculate the image pixel distance between the star \( S_i \) and the projected star \( S_j \).

\[
d_i = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}
\]

When \( d_i \) is the smallest, star \( S_i \) in the field of view and \( S_j \) in the catalogue are considered as the same one, its magnitude information can be inquired from the catalogue.

3.3. Calculation method of target magnitude

Star magnitude is defined as that two targets' difference of illuminance is 100 times when 5 magnitude difference. The target's magnitude \( m_a \) is related to the logarithm of its light energy \( E_a \) and the relationship as following.

\[
m_a \propto -\lg E_a
\]

For two targets with 5 magnitude difference,

\[
m_a - m_b = -k \lg \frac{E_a}{E_b} = -k \lg \frac{1}{100} = 2k = 5
\]

So, \( k = 2.5 \).

Due to the real-time change of the extinction, the measuring error of target magnitude is large. If the target to be measured and a star with known magnitude are in the same field of view, they are affected by the same atmospheric extinction. According to (14), the relationship between target
magnitude $m_r$, star magnitude $m_s$, target imaging energy $E_r$ and star imaging energy $E_s$ can be expressed as

$$m_r = m_s + 2.5\lg \left( \frac{E_s}{E_r} \right)$$

(15)

This is the principle of the target photometry measuring by the antitheses method. Therefore, the known star can be used to eliminate the influence of atmospheric extinction and obtain the accurate target magnitude.

Under the condition of invariable optical system and integration time, the relationship between target imaging gray value $D_T$ and imaging energy $E_T$ can be approximately regarded as a linear relationship. So

$$m_r = m_s + 2.5\lg \left( \frac{D_s}{D_T} \right)$$

(16)

The target gray value $D_T$ and star gray value $D_s$ are obtained by the above-mentioned image processing method, the star magnitude $m_s$ is obtained by star catalogue query.

It should be pointed out that the linear relationship between gray value and imaging energy is not tenable when the image is over exposed and the target magnitude estimated by this method would have a large error.

4. Experimental results

4.1. Software implementation

The proposed target photometry measurement method is implemented. The software interface is shown in Figure 2, which is mainly divided into two areas: the left area is all kinds of operation buttons, the right area is the display area of the actual imaging image, as well as used for the projection of stars in the catalogue and the calculation of imaging gray value.

![Figure 2. Interface of the implemented software.](image)

| Observation time | Star | Magnitude (Mv) | Gray value | Magnitude (Mv) | Error (Mv) | Relative error |
|------------------|------|----------------|------------|----------------|------------|---------------|
| 2018.12.08       | A    | 9.10           | 1532       | 9.19           | 0.09       | 1.0%          |
| 02:42            | B    | 6.42           | 19687      | 6.33           | 0.09       | 1.4%          |
| 2018.12.08       | A    | 7.79           | 1968       | 7.86           | 0.07       | 0.9%          |
| 02:45            | B    | 8.70           | 910        | 8.63           | 0.07       | 0.8%          |
| 2018.12.08       | A    | 5.79           | 13973      | 5.96           | 0.17       | 2.9%          |
| 02:46            | B    | 7.17           | 4565       | 7.00           | 0.17       | 2.3%          |
| 2018.12.08       | A    | 6.33           | 7334       | 6.80           | 0.47       | 7.4%          |
| 02:46            | B    | 7.17           | 5203       | 6.70           | 0.47       | 6.5%          |
| 2018.12.25       | A    | 6.91           | 4275       | 7.37           | 0.46       | 6.7%          |
| 01:18            | B    | 7.52           | 3722       | 7.06           | 0.46       | 6.1%          |
4.2. Target magnitude measuring results

Using the scene shown in Figure 2, that is, when two stars appear at the same time in the field of view, experiments are carried out to investigate the accuracy of the proposed target magnitude measuring method.

Five groups of tests are carried out and the detailed results are shown in Table 1. The actual magnitude of stars in the table is obtained by the method in Section 2.3, and the imaging gray value is obtained by the method in Section 2.1. Finally, the measured value of star magnitude and measuring error are calculated.

It can be seen from the experimental results that the absolute error of the target magnitude measured by the proposal method is no more than 0.5Mv while the relative error is less than 8%. The measured target magnitude has certain reference value in practical application.

5. Conclusion

Aiming at the application scene of small view field and simple imaging content of the photoelectric theodolite on a survey ship, this paper studies and realizes a method by using stars in the same field of view to measure the target magnitude conveniently and quickly. Firstly, the image processing technique is employed to calculate the gray value of the target and the stars in the same image. Secondly, the ship's position, pose information and the theodolite angle information are used to calculate the direction of the optical axis of the theodolite in the celestial coordinate system, and then stars in the pre-processing catalogue are projected on the image to determine the star magnitude. Finally, the principle of the antitheses method is adopted to calculate magnitude of the observed targets. The method is implemented and a cross validation photometry experiment is carried out. The results show that the relative error of the target photometry calculated by the proposed method is less than 8% and indicate its practical value in engineering practice.

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