A New Target Reconstruction Method Considering Atmospheric Refraction

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ABSTRACT

In this paper, a new target reconstruction method considering the atmospheric refraction is presented to improve 3D reconstruction accuracy in long rang surveillance system. The basic idea of the method is that the atmosphere between the camera and the target is partitioned into several thin layers radially in which the density is regarded as uniform; Then the reverse tracking of the light propagation path from sensor to target was carried by applying Snell's law at the interface between layers; and finally the average of the tracked target's positions from different cameras is regarded as the reconstructed position. The reconstruction experiments were carried, and the experiment results showed that the new method have much better reconstruction accuracy than the traditional stereoscopic reconstruction method.

Keywords: atmospheric refraction, the stereoscopic reconstruction, Snell's Law, the total reflection, Hopfield refractivity model

1. INTRODUCTION

In long range surveillance system, the position of target is the key information about the target, and usually acquired through the stereoscopic reconstruction method with the binocular stereo vision .

Up to now, a great deal of methods has been put forward to reconstruct the position of target. The original method proposed in [1] is that to reconstruct the position of target based on the principle of triangulation, the 3D information of the target can be recovered by its vision disparity from the two images. Since this method has been proposed, many improved methods are put forward [2] ~ [6]. But all these methods ignore the effect of atmospheric refraction and regard the propagation path of light as linear when reconstructing. However, in long range surveillance system, the atmosphere between the target and sensor will have significant effect on the propagation of the light, and the ignorance of atmosphere effect would lead to much large reconstruction error. To improving reconstruction accuracy, a new reconstruction method considering the atmospheric refraction was proposed.

The atmospheric refractivity, which is a crucial factor in the proposed method, is related to the temperature, the relative humidity, the pressure of atmosphere etc., and the relationship can be defined by Smith and Weintraub Formula [7]. However, due to the computation complexity of the Formula, many simplified atmospheric refraction models were proposed [8], such as Linear Model, Exponential Model, Double Exponential Model and Hopfield Model etc. And each model has its scope of application, for instance, the Linear Model only applies to the lower altitude, and the calculation accuracy of Exponential Model is not as well as the Double Exponential Model and Hopfield Model. Over all, Hopfield Model has much better comprehensive performance on application scope and calculation accuracy [9], and has been selected to compute the atmospheric refractivity in the paper. Studies show that the atmospheric refractivity in horizontal direction is smaller than that of vertical direction by 1~3 order of magnitude [10]. The atmospheric refraction in the horizontal direction was usually ignored and only the atmospheric refraction in vertical direction was taken into account.

2. METHODOLOGY

It is assumed that the distribution of atmospheric density is concentric and the density is uniform along tangential direction but varied in earth radial direction. The main idea of our new method is that the atmosphere between the camera and the target is partitioned into several thin layers radially in which the density is regarded as uniform, the reverse tracking starting at position of camera with the incident of the light from the target was carried to obtain the whole propagation path of light from the target by means of that the direction of the light through the border between the two thin layer is determined by Snell's law, and the intersection point of the paths tracked from the two cameras is

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regarded as the reconstructed position of the target. And in the calculation of propagation path of light we also consider the total reflection of light. The new method contains the flowing steps:

STEP 1: Computation of the direction vector from the camera to the target: with the image position (u, v) of the target in the row × col images, the camera's position $C_1(x_1, y_1, z_1)$ and the camera's pointing $\vec{P}$, the direction vector $\vec{V}$ of light from the camera to the target can be given as:

$$\vec{V} = M * Vec$$

Here, M is the transition matrix from camera coordinate system to the geocentric coordinate system; Vec is the vector of light in the camera coordinate system and can be calculated as:

$$Vec = \begin{bmatrix} \cos\theta_1 & 0 & \sin\theta_1 & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\theta_1 & 0 & \cos\theta_1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta_2 & -\sin\theta_2 & 0 \\ 0 & \sin\theta_2 & \cos\theta_2 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} 0 \\ 0 \\ 1 \\ 1 \end{bmatrix}$$

Here, $\theta_1 = (u - row/2) * \eta$, $\theta_2 = (v - col/2) * \eta$ and η is the camera's instantaneous field of view. In this step, the camera coordinate system is defined as flowing: the origin of coordinate is the position of camera; X-axis is perpendicular to the plane composed of camera, target and the earth's core; Z-axis is coincident to the camera's pointing $\vec{P}$; Y-axis is fixed by right-hand screw rule.

For the camera C_1 and C_2, the corresponding direction vectors of light are $\vec{V_1}$ and $\vec{V_2}$ respectively.

STEP 2: **Determination of the line on which the target is**: the target is located in the intersection line of two planes OC_1P determined by geocentric O ,camera position $C_1(x_1, y_1, z_1)$ and target position P, and the plane OC_2P determined by geocentric O, camera position $C_2(x_2, y_2, z_2)$ and target position P.The normal vectors of the two planes $\vec{N_1}$ and $\vec{N_2}$ are given as

$$\vec{N_1} = \vec{V_1} \times \vec{OC_1}, \ \vec{N_2} = \vec{V_2} \times \vec{OC_2}$$

The direction vector $\vec{d}_{OP'}$ of the intersection line is the cross product of the two normal vectors as $\vec{d}_{OP'} = \vec{N_1} \times \vec{N_2}$.

STEP 3: Reverse tracking of the propagation path: For camera C_1, to simplify the computation of the tracking path, a new coordinate system is defined where the origin is the geocentric; and X-axis is consistent with the intersection line of plane OC_1P and plane OXY of the geocentric system; Y-axis is perpendicular to plane OC_1P ; and the Z-axis is fixed by right-hand screw rule. The transformation from the geocentric coordinate system to our new coordinate system simplifies the 3D path tracking to 2D path tracking in plane OC_1P. After the transformation, the path tracking is carried with the following steps:

Step 3.1: The geocentric angle θ_1 between target and camera C_1 can be computed as:

$$\theta_1 = \arccos\left(\frac{\vec{OC} \cdot \vec{d}_{OP'}}{\left|\vec{OC}\right| \left|\vec{d}_{OP'}\right|} \right)$$

Divide the geocentric angle θ_1 into N_1 same small angles and each angle $d\theta = \theta_1 / N_1$; correspondingly, the atmosphere between target and camera C_1 is also divided into N_1 tiny layers, as shown in Fig.1. The layer which camera C_1 is in is considered as the first layer.

Step 3.2: (1) While the light goes through the border between the i^{th} layer and the $(i+1)^{th}$ layer (where i=1, 2…, n_1), as shown in Fig.1. The vector of incident direction $\vec{v_i}$ is also the vector of emergent direction of previous border, the incident angle α_{i+1} at the incident point T_{i+1} is calculated as:

$$\alpha_{i+1} = \arccos\left(\frac{\vec{OT}_{i+1} \cdot \vec{v_i}}{\left|\vec{OT}_{i+1}\right| \cdot \left|\vec{v_i}\right|} \right)$$

(2) The angle of emergence β_{i+1} is calculated by Snell's Law: $\beta_{i+1} = \frac{n_i}{n_{i+1}} \sin \alpha_{i+1}$, where the atmospheric refractivity n_i, n_{i+1} can be computed with Hopfield refractivity model.

(3) The unit vector of the direction of emergence $\vec{u_e} = (u_x, u_z)$ is calculated by:

$$\begin{cases} \cos \beta_{i+1} = \dfrac{\vec{u_e} \cdot \vec{OT}_{i+1}}{\left|\vec{OT}_{i+1}\right|} \\ u_x * u_x + u_z * u_z = 1 \end{cases}$$

(4) Finally, we get the vector of emergent direction $\vec{v}_{i+1}$ as $\vec{\mathrm{v}}_{i+1} = L_{i+1} \vec{u_e}$, where L_{i+1} is the length of light path in $(i+1)^{th}$ layer, which can be computed via triangle $OT_{i+1}T_{i+2}$ as following: $L_{i+1} = \frac{\left|\vec{OT}_{i+1}\right| \sin(d\theta)}{\sin(\beta_{i+1} - d\theta)}$. And the position of the incident point of next border T_{i+2} is given as $T_{i+2} = T_{i+1} + \vec{v}_{i+1}$.

In the calculation of each layer's propagation path, we also consider the total refraction of light to make the path closer to actual and the position of target more accurate. The path of light's total refraction is calculated as following:
In each layer, if $n_i > n_{i+1}$ and the incident angle α_{i+1} calculated in Step 3.2 satisfies: $\alpha_{i+1} \geq \arcsin\left(n_{i+1}/n_i\right)$. The light doesn't refract into next layer, but total reflect into next layer instead. According to the Law of Total Reflection, the angle of reflection ε_{i+1} is equal to the incident angle α_{i+1}. This can be regarded as that the angle of emergence β_{i+1} can be calculated as: $\beta_{i+1} = \pi - \alpha_{i+1}$. The later calculation of this layer is the same as Step 3.2 (3), (4).

The layer which camera C_1 is in is considered as the first layer. The initial of $\vec{v_i}$ is the direction vector $\vec{V_1}$ calculated in step1, and the initial of T_{i+1} is the position of camera C_1. Since each layer is thin and the density of atmosphere in each one is regard as uniform, the atmospheric refractivity of each layer is equal to that of the incident position of each. The initial of n_{i+1} can be calculated by the position of camera C_1 with the Hopfield refractivity model and the initial of n_i is equal to n_{i+1}.

Step 3.3: While the number of layer is equal to N_1, the position where the light goes into the next layer is the tracked position of target $P_1^{'}$.

For another camera C_2, we can use the same method as camera C_1 to calculate the position of target $P_2^{'}$.

STEP 4: Get the position of target: for more accurate result, the final position of target P is the average of the positions $P_1^{'}$ and $P_2^{'}$: $P = \left(P_1^{'} + P_2^{'}\right)/2$.

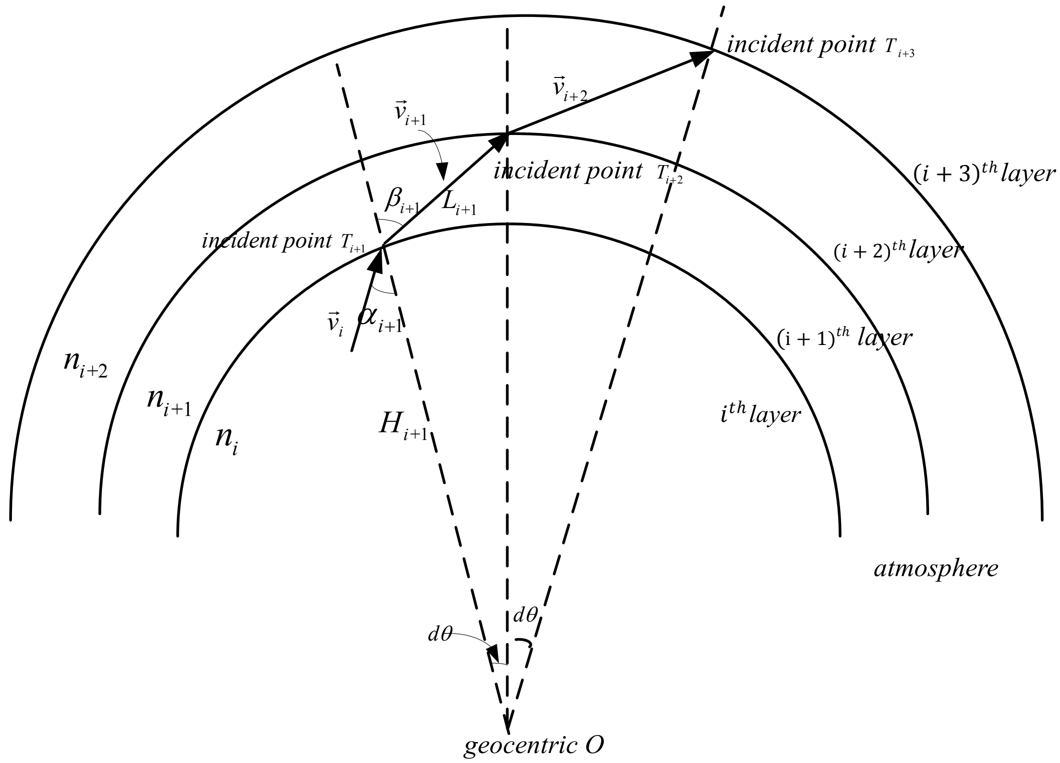
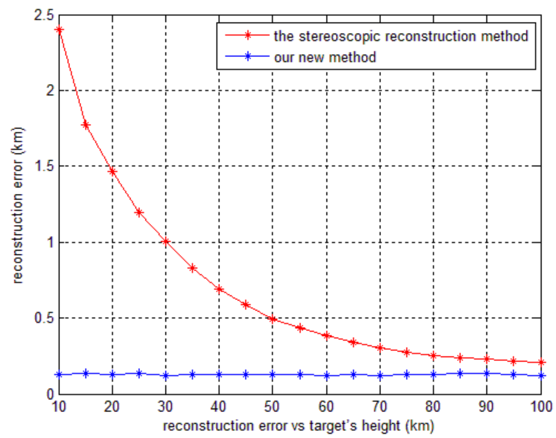


Fig.1 The propagation path of light in each layer

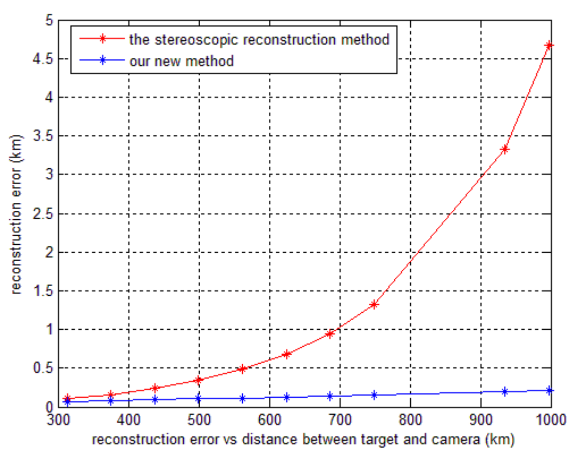
3. EXPERIMENTAL RESULTS

Given the positions $C_1(x_1, y_1, z_1)$, $C_2(x_2, y_2, z_2)$ of the two cameras, the corresponding pointing $\vec{P_1}$, $\vec{P_2}$ and the image position of the target $(u_1, v_1), (u_2, v_2)$, the target position can be reconstructed according to the steps described in previous section. In the reconstruction experiments, with the assumption that the errors obey Gaussian distribution $N(0, \sigma)$ independently, the errors of camera pointing, imaging platform's posture and target's image position were applied with the standard deviations 0.00167°, 0.00667° and 0.33pixel respectively. The reconstruction error which is the Euclidean distance between the reconstructed position P_n and the real position P was used to measure the method's performance. The reconstruction error of the proposed method was also compared to the traditional stereoscopic reconstruction method. In the calculation of atmospheric refractivity with Hopfield model, the atmospheric parameters of different places are calculated from the USSA-1976 [11].

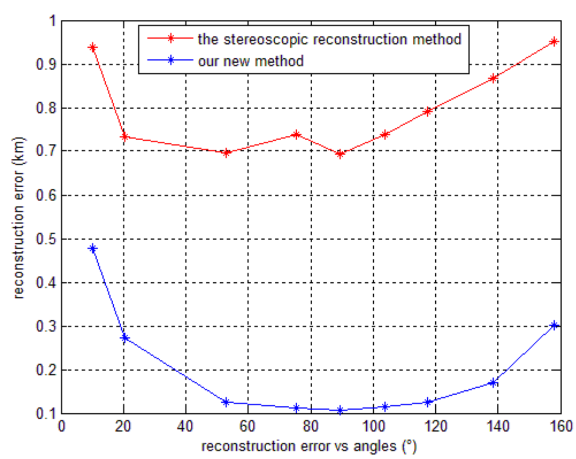
Three factors which are the height of target from the ground, the angle between two cameras' pointing and the distance between the camera and the target were taken into account, and the relationship between the reconstruction error and the factors were explored respectively. The 3 different experiments were conducted with Control variable method, In each experiment, only one factor can be changed, and the others were fixed. **Experiment (a)**: The changing factor is the height of target from the ground, the height of cameras from the ground is 20 km, and the result is shown in Fig.2-(a). **Experiment (b)**: The distance between the target and the camera is changed, and the height of target and the angle between the two cameras' pointing were 30 kilometers and 53° respectively. The result was shown in Fig.2-(b). **Experiment (c)**: The angle between the two cameras' pointing was varied, and the height of target and the distance between the target and the camera were 30 km and 640 km respectively. The experiment result was shown in Fig.2-(c).



(a) reconstruction error vs target's height



(b) reconstruction error vs distance between target and camera



(c) reconstruction error vs angles

Fig.2 The reconstruction error of the two methods

As shown in Fig.2-(a), the reconstruction error of the new method is about 100 meters and maintains constant with the varied height of target. However, the stereoscopic reconstruction method has larger error than the proposed method, its reconstruction error is inversely proportional to the height of target, and can be more than 2 kilometers at the height less than 20 km. So the conclusion is come to that the atmospheric refraction has a great effect on the path of light, especially when the altitude is low. If the influence of atmospheric refraction is ignored, the result of reconstruction will not be accurate. As shown in Fig.2-(b), the reconstruction error of the new method is enlarged very slowly with the increasing of the distance between the target and the camera, no more than 200 meters at the distance 1000 km, comparatively, the error of the traditional stereoscopic reconstruction method increases rapidly with the distance, and reaches over 4.5 km at the distance 1000 km. The experiment shows that the proposed method is not very sensitive to the distance between the target and the camera. Fig.2-(c) explored the relationship between the reconstruction accuracy and the angle between the two cameras' pointing. Similar to the traditional stereoscopic reconstruction method, when the value of angle is between 50° and 120°, the new method has the smallest reconstruction error. All of the experiments shows that the error of the proposed method is much smaller than the traditional stereoscopic reconstruction method, by taking into account the atmospheric refraction, the reconstruction accuracy can be improved greatly.

4. CONCLUSIONS

When the range between the target and the sensor is very long, the atmospheric refraction will have a great effect on the propagation of light especially when the altitude is low. The ignorance of the refraction effect would lead to large error on the reconstructed target's position. Reverse tracking based reconstruction method was proposed, in which both the refraction and total reflection are taken into account. Comparing with the traditional stereoscopic reconstruction method, the method reduced the reconstruction error greatly, especially when target was at low altitude. The error usually was not no more than 300 meters. Experiments explored that the error of the proposed method was not subject to the variation of the target's range and altitude, and the stereoscopic reconstruction method, the proposed method would achieve better performance when value of the angle between the two sensors' pointing is among 50° and 120°. In summary, due to that the atmospheric refraction has been taken into account in the reverse tracking of light propagation, the proposed method improves the reconstruction accuracy greatly.

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