Application of Ray Following Algorithm to High Resolution Satellite Image Simulation

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Abstract : This paper describes a new algorithm named as ray following algorithm which is applied for high-resolution satellite image simulation. The problems of the conventional ray tracing algorithm are pointed out especially when terrain elevations vary abruptly. The proposed algorithm follows the directional ray vector sequentially and thoroughly in order to determine the crossing point of the ray with the terrain surface. This way of sequential height comparison method is regarded as the only way to obtain accurate surface cross-section when a highly variant digital surface model is used. The experimental results show and compare the validities of the conventional and proposed algorithms.
Key words : camera model, direct mapping, ray following, image simulation

1. Introduction

A procedure which sets up a relationship between image coordinates and the corresponding geographic coordinates on Earth surface is called camera modeling. In the past, the camera modeling studies have been approached from two different imaging scales: microscopic and macroscopic. The microscopic approach has been based on a photogrammetric modeling which uses a set of collinearity equations. The original collinearity equation was established for modeling aerial photographs. As medium resolution spaceborne imaging systems such as SPOT have been realized, a number of modified versions of the collinearity equation have been proposed in order for modeling moving focus of a pushbroom-type sensor, attitude variation, Earth curvature and rotation. On the other hand, macroscopic modeling approaches have been made for low resolution imaging systems such as NOAA/AVHRR in which a complete orbit dynamics, perturbation and attitude control mechanism are fully in concern. These imaging navigation models have mainly focused on automatic and operational image geometry correction while the photogrammetric modeling concerns mainly on accurate topographic mapping. As 1m resolution spaceborne optical sensors have become available commercially, the application boundary between the two types of the modeling techniques becomes unclear.

Regardless of what type of camera model is used, the model can be represented by a focal point in the imaging sensor, a target point on Earth surface and a ray connecting the two points. The ray is generally modeled as a straight line unless a high-order physical modeling such as atmospheric refraction is considered. The procedure which determines unknown target point coordinates by using known focal point and ray parameters is called direct (or forward) modeling. On the other hand, the procedure which determines unknown focal point coordinates as well as the direction of the ray by using known target point coordinates is called indirect (or inverse) modeling. Unfortunately, neither direct nor indirect modeling can be solved deterministically because of the non-linear time-varying orbital path of a pushbroom-type sensor and non-systematic variations in terrain surface. The nature of non-linear modeling requires a number of iterations in order to obtain a converged solution.

One of the main purposes of the camera modeling is the generation of geographically rectified images such as ortho-images. In this case, the regularly spaced brightness values in the image domain are mapped onto the regularly spaced Earth surface domain by using a camera model and a suitable map projection scheme. Chen and Lee (1993) described the disadvantage of using direct modeling when it is applied to orthophoto generation: iterative computation and incorrect gray value mapping. The latter problem of the direct modeling results in the degradation of the final product quality especially where the projected target positions shows very irregular distribution in comparison with the target grid.

The simulated image generation process is a completely reverse engineering of the ortho-image generation process. Before a spaceborne imaging sensor is launched and operated, the corresponding simulated images are generated and provided in order for future data users to develop application algorithms. In this case, the brightness values on the image coordinate grid should be determined by a previously generated ortho-image as well as Earth surface terrain height information. Therefore, the problem of the incorrect gray value mapping which was described in the previous paragraph is applied identically to the indirect modeling (not to the direct modeling) in the simulated image generation process. Conclusively, it is required to use direct modeling in order to obtain a simulated image which would have brightness values closer to a real image.

The direct modeling technique has to use a ray tracing algorithm for determining a three dimensional target position. The ray tracing algorithm, however, retains major problems when it is applied to the terrain model which has abrupt height variations. The main focus of this paper is to address the problems of the ray tracing algorithm and to propose a new scheme, a ray following algorithm, for high-resolution simulated image generation.

2. Problems on Ray Tracing Algorithm

The graphical illustration of the ray tracing algorithm is shown in Figure 1 (O'Neil and Dowman, 1988). As shown in Figure 1 (a), the ray is supposed to be traced to the correct target point on the surface. This convergence does not happen in the case where the slope of the surface is higher than the inclination angle of the ray as shown in Figure 1 (b). In this case, the algorithm stays in an infinite iteration rather than terminating with a divergence condition. In addition, the ray tracing algorithm converges to a wrong destination if the ray crosses the surface at more than one point (Figure 1 (c)). The obscuring target position (A) is misinterpreted as (B), so that an incorrect brightness value is assigned.

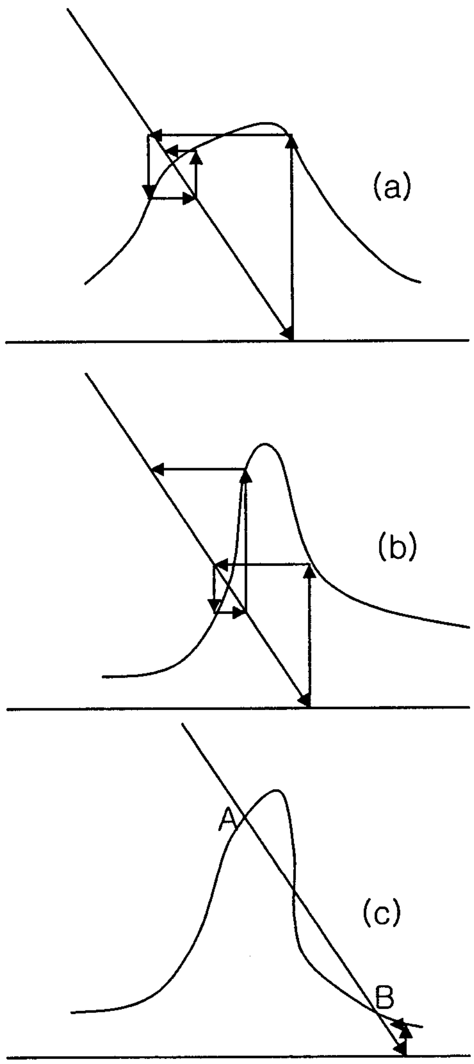

Figure 1. Conventional Ray Tracing Algorithm

These two problems of the conventional algorithm occur when the terrain elevation varies rapidly in a spatial domain. While the digital elevation model (DEM) of a medium resolution shows smooth and continuous variation, high-resolution (e.g. less than 1m) digital surface model (DSM) contains a large amount of height discontinuities in general. Therefore, the ray tracing algorithm cannot be applied to the current work scope of the high resolution image simulation.

3. New Approach - Ray Following Algorithm

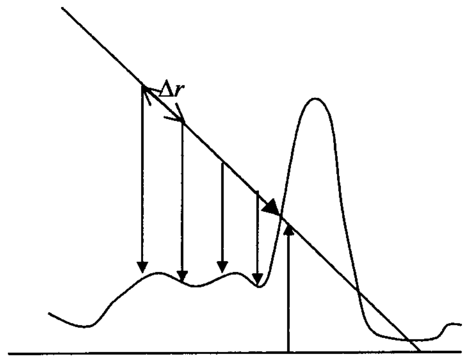

Figure 2. Ray Following Algorithm

The concept of the proposed ray following algorithm is simple and thorough. Figure 2 illustrates the terrain surface with an abrupt height discontinuity where the conventional ray tracing algorithm results in an incorrect convergence (Figure 1 (c)). The ray following algorithm follows the ray from top to bottom and compares the height of the surface with the height of the point on the ray. The ray following is terminated when the surface height is greater than the height of a certain point on the ray. The point would be the result of the direct modeling. By using the sequential ray following technique, the oscillation problem and the mismatch problem of the conventional ray tracing algorithm for the high resolution DSM can be solved completely.

The mathematical modeling of the ray tracing and the ray following algorithm would be very simple if a photogrammetric approach is used. In this case, a DSM on a flat Earth model is used so that the terrain height and the ray crossing point can be determined by controlling the "z" variable. However, it is highly required to adopt an ellipsoidal Earth model as well as a DSM with respect to the latitude/longitude grid for 1m resolution satellite images in order to obtain more accurate geographic representation. In this sense, the Earth Centered of Rotation (ECR) reference frame is used for modeling all non-linear features of the platform path and the Earth ellipsoid.

The ray can be represented as a straight line as follows,

$$P = (x, y, z) = r(x_d, y_d, z_d) + (x_s, y_s, z_s) \quad (1)$$

where (x_d, y_d, z_d) is the normalized directional vector of the ray and (x_s, y_s, z_s) is the position of the focal point (position of the satellite for simplicity). The real value variable, r, determines the size of the ray, i.e. distance between the satellite and the target. Therefore, the ray can be followed by controlling the variable r.

It is also required to obtain the terrain heights which correspond to the ray-following points. Since a DSM is generally based on the latitude/longitude grid, the ECR coordinates of the ray points, (x, y, z), are required to be converted to the latitude (ϕ), longitude (λ) and height (h) as follows (Dana, 1997),

$$\begin{aligned} \theta &= \tan^{-1}\left(\frac{za}{b\sqrt{x^2+y^2}}\right) \\ \phi &= \tan^{-1}\left(\frac{z+\frac{a^2}{b^2}e^2\sin^3\theta}{\sqrt{x^2+y^2}-e^2a\cos^3\theta}\right) \\ \lambda &= \operatorname{atan2}(y,x) \\ h &= \frac{\sqrt{x^2+y^2}}{\cos\phi}-\frac{a}{\sqrt{1-e^2\sin^2\phi}} \end{aligned} \quad (2)$$

where a, b, e are the semi-major, the semi-minor and the eccentricity of the Earth ellipsoid, respectively. If the DSM is based on a datum other than WGS-84, a datum conversion process is required. In addition, a geoid model should be added if the height level of the DSM is based on the mean sea surface level rather than the above-ellipsoid level.

The proposed ray following algorithm can be summarized in terms of the following steps.

Step 1 : determination of initial parameters.

This step determines the $r_{\min}$ which corresponds to the starting point on the ray. This value is determined by a simple triangular geometry,

$$r_{\min} = H_{\max} / \sin(\theta_i) \quad (3)$$

where $H_{\max}$ is the maximum height of the DSM and θ_i is the incident angle of the ray on the Earth ellipsoid. $H_{\max}$ is determined either by a priori knowledge or by finding the maximum height value on the DSM grid. If the incident angle, θ_i, is 90°, the latitude, longitude and height of the initially projected point is returned and no more steps are required. Otherwise, r is initially set to $r_{\min}$. In addition, Δr which is the discrete step of r for the ray following is determined in this step. As Δr becomes smaller, the algorithm requires more intensive computations. In opposite, a large Δr may result in missing a DSM spike. In this sense, Δr is determined by the horizontal resolution of the DSM grid, as follows.

$$\Delta r = D_{DSM} / \cos(\theta_i) \quad (4)$$

Step 2 : determination of current ray point coordinates.

In this step, the ECR coordinates of the current point on the ray, (x, y, z), are determined from Eq. (1) by using the current value of r and they are converted to the latitude/ longitude/height coordinates (ϕ, λ, h) by using Eq. (2).

Step 3 : obtaining terrain height.

The terrain height above ellipsoid, H, is obtained from the DSM.

Step 4 : height comparison.

If the terrain height of the ellipsoid (H) is larger than the height of the current ray point (h), the algorithm is terminated. This condition means that the ray hit the first point of the terrain surface. The final result of the direct modeling, i.e. (ϕ, λ, h), is refined by using the results of the previous and the current ray points. If this condition is not satisfied, the algorithm continues to the step 5.

Step 5 : current ray point update.

The position of the current ray point moves downward by a pre-defined discrete step.

$$r = r + \Delta r \quad (5)$$

Then, the algorithm is iterated by going back to Step 2.

4. Experiment

An aerial ortho-photo was resampled to have 1m resolution and a coarse DEM was used as a base elevation model. On top of the coarse DEM, four buildings were selected and modeled as polygons and different height was assigned to each polygon. This test image and DSM was used for the simulated image generation in which a north-bounding satellite scans the test image with a viewing angle of approximately 9 degree from East to West. This situation is shown in Figure 3.

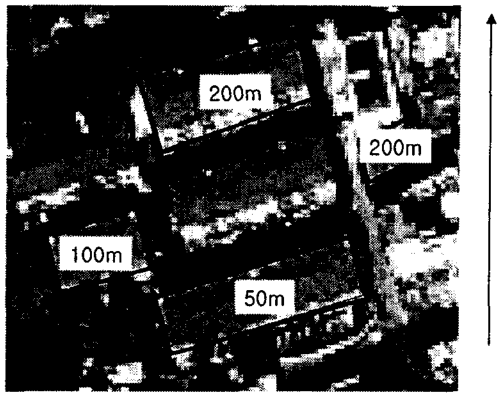

Figure 3. Test image, polygons and direction of satellite

The resulting simulated images are shown in Figure 4. The image generated by the ray following algorithm shows accurate disparities on the top of the polygon buildings (Figure 4(a)). The side of the buildings are also shown clearly due to the oblique viewing of the satellite. Since no gray-level information about the side of the buildings was provided from the original ortho-photo, the gray values of polygon boundaries were interpolated and assigned. The occluded regions due to the neighboring high buildings are also shown. On the other hand, infinite iteration occurred when the ray tracing algorithm was applied (white regions in Figure 4(b)). In addition, the surface hitting points were incorrectly converged to the base elevation, not to the top of the building, so that no building top disparities nor building sides are shown in the simulated image.

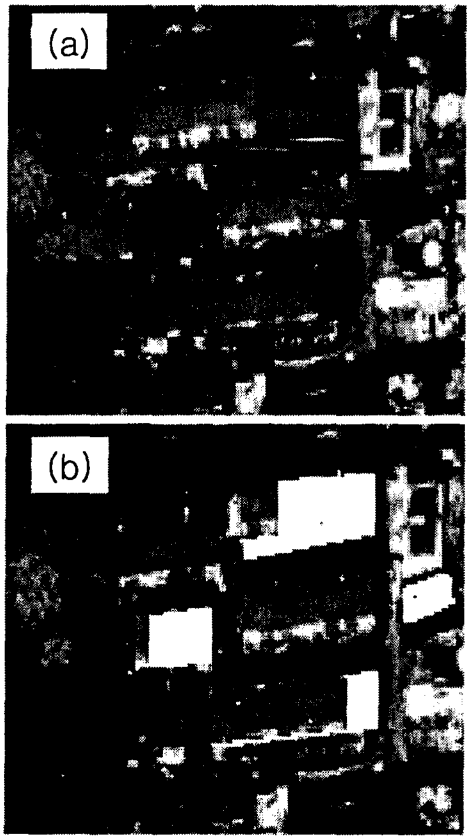

Figure 4. Simulated images : (a) ray following algorithm, (b) ray tracing algorithm

5. Conclusions and Discussions

This paper described a simple and thorough ray following algorithm for the high-resolution satellite image simulation. The advantage of the direct modeling on the resampled image quality over the indirect modeling was described by mentioning the reverse engineering nature of the image simulation. On the application to the high-resolution satellite images, the two major problems of the conventional ray tracing algorithm, i.e. infinite iteration and incorrect convergence, were pointed out. A new ray following algorithm was introduced and verified for solving the problems of the ray tracing algorithm.

The processing time of the proposed algorithm is worth being discussed at this point. The sequential search method of the algorithm requires a number of iterations until the ray hits the terrain surface. Since this study assumes high-frequency variations of the terrain height and hence the ray may crosses the terrain surface at many points, other tracing algorithms which may provide more efficient search methods, e.g. binary or tree search, cannot be applied Any intelligent tracing algorithms may result in the incorrect convergence due to the irregularity of the high-frequency terrain surface. In conclusion, the proposed sequential ray following algorithm is the most robust and error-free algorithm compared with other algorithms which may use adaptive schemes in order to reduce the computations. Most of all, the current study does not concern with the processing time because the purpose of this study, i.e. simulated image generation, is not related to any operational use of the proposed algorithm.

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