Simulation and 3D Visualization of Mission Scheduling for Imaging Satellites

Baosong Deng, Rongfu Tang*, Jing Li and Erwei Yin

Unmanned Systems Research Center, National Innovation Institute of Defence Technology, Academy of Military Sciences, Beijing, China.
Email: dbs310@163.com

Abstract. Simulation, 3D visualization and analyses of satellite imaging tasks are capable to display orbital maneuver and ground cover scheme, which are much helpful to ensure the feasibility and reliability of the mission planning and to improve the efficiency of the satellite utilization. A system of 3D visualization and simulation for satellites is proposed and presented in the current work. Multi-resolution mass terrain data, images and vector data are processed and seamless stitched, and dynamic roaming of large range scenes based on digital earth is built as well. Then, the satellite flight status, maneuver, onboard sensor states and ground coverage ranges are visualized by using data of the satellite mission scheduling. Moreover, the system provides the visualization analyses of multi-dimension, high fidelity, free observation and so on. The proposed system is evaluated by practical satellite data and the experiments show that the system is capable to offer an intuitive, convenient and effective way for the space exploration and engineering design of satellites.

1. Introduction
Remote sensing satellites have many advantages, such as wide imaging range, repeatable observation and safe and legitimate access. They are widely used in many fields and occupy a large proportion in many spacecraft. In the process of spacecraft orbit design and mission planning, a large amount of data (such as satellite state, parameter control, etc.) will be generated. By using visualization technology and simulation program, the actual satellite orbit scene can be constructed based on the effective data such as orbit parameters, position status, thus the satellite reality can be accurately described and reproduced. Time operation and attitude provide very direct guidance for satellite applications such as space mission planning and demonstration, orbital analysis and design, and operation status monitoring[1]. In addition, the mission planning of imaging satellites is a very complicated problem, and the rationality and correctness of the planning scheme is directly related to the rational utilization of satellite resources and the full utilization of satellite imaging efficiency. Therefore, it is necessary to carry out visual simulation to ensure its reliability and efficiency, and provide visual decision support for decision makers[2].

The research on satellite system simulation started earlier abroad, and a variety of relatively mature commercial simulation software was developed. Among them, the more general is the STK satellite simulation analysis toolkit of AGI Company, which is the leading commercial analysis software of aerospace industry. It can analyze complex space missions quickly and conveniently, and provide chart and text analysis results, to facilitate users to determine the best solution. However, STK provides relatively limited functions of 3D visualization graphics development kit[3], especially in the display effect and professional 3D graphics engine still has a big gap; its ability to load digital earth high-definition terrain, images and vector tiles is obviously inadequate, unable to achieve satellite
scheduling planning tasks and high-fidelity, massive terrain images. The direct alignment of images and the flexibility of the two development of graphical interfaces are not enough[1].

In addition, because the three-dimensional simulation method can more intuitively, vividly reflection the space three-dimensional situation of the aircraft and its scanning range is compared with the real terrain and landform. The results of the simulation application are more sufficient under the stereo vision performance, so the space three-dimensional simulation in the satellite mission planning, state plays an increasingly important role in potential assessment and decision making.

2. System Framework Design
The design of visualization simulation system for imaging satellite task scheduling must ensure the portability of platform and function modules, ensure relative independence through serial connection between protocol interfaces, and avoid the lack of universality due to strong coupling. In addition, it should have the ability to demonstrate the imaging process of multiple satellites, be able to perform dynamic deductions based on astronomical time, and support the assessment of mission planning effectiveness.

The overall framework of the system is shown in Figure 1. Relying on the simulation computing environment, and based on the input imaging plan description script or simulation instructions, the satellite-related simulation control data are calculated and generated. These data are transmitted to the three-dimensional visual simulation system through the network environment, and the visual results of imaging satellite scheduling are realized on the basis of digital earth.

Visual simulation of satellite mission planning involves many aspects, including satellite imaging plan, payload control plan, ground station tracking and receiving plan, data transmission plan and so on. Among them, the payload control plan refers to the satellite load action and the corresponding action execution time, such as swing, switch, data download, etc. To control the operation of the satellite, tracking and receiving plan refers to a series of actions such as when the satellite enters and leaves the station, when the ground station receives data, and when to inject commands into the satellite. Visual simulation system is to vividly demonstrate the satellite's operation environment, imaging scheme and other specific actions, and fully reproduce the real scene.

3. 3D Earth Seamless Roaming
In astronomical observation, the celestial sphere coordinate system is generally used to describe and express. In astronomy, the celestial sphere is an imaginary sphere with an infinite radius theoretically. In this paper, the center of the celestial sphere is the center of mass of the earth. Therefore, the focus of this paper is the visualization of the earth and the surrounding space environment. In addition, the key reference object and the final imaging target of satellite mission scheduling simulation are the earth. Therefore, it is very important to build a realistic three-dimensional digital earth based on real digital terrain, high-definition images and key vector data for remote sensing satellite simulation, which also provides an important reference for the verification of mission scheduling scheme.

3.1. Data Preprocessing
In browsing massive terrain or model data, it is often necessary to use LOD (Level of Detail) technology to pre-partition them to ensure that the data structure can be dynamically scheduled. LOD
is to decide the resource allocation of object rendering according to the position and importance of model nodes in the 3D environment under certain viewpoint parameters, and reduce the details of non-important objects, i.e. the number of meshes, so as to speed up scene rendering and ensure the dynamic balance of data in the 3D scene. Usually geometric models are loaded from files into memory at one time, but for massive terrain data - hundreds of GB or even TB level, the computer memory capacity cannot be fully accommodated.

![Image](image_url)  
**Figure 2. Data processing flow**

At present, the commonly used solution is memory dynamic scheduling mechanism, that is, massive data paging technology, only display the scene elements in the current horizon at the same time, preload the next possible visible data, and then remove the data from the horizon from memory, through this form of dynamic scheduling, to ensure that the memory always dimension. A limited amount of data is used to make the scene browsing without losing information or being too slow.

Figure 2 shows the data preprocessing flow. After the coordinate transformation of different resolution elevation, image and vector data, bilinear interpolation resampling is carried out according to the pre-set scale. The tile data of different layers are constructed and provided to the dynamic loading thread by file service. Among them, elevation data is used to construct the earth surface topographic spatial grid, and high-resolution image data is used to reproduce the realistic and clear surface environment by texture mapping. All these data are constructed in the form of quad tree spatial tile data services to ensure real-time dynamic loading on demand. Vector data can clearly mark the boundaries of administrative divisions, rivers and key terrain information, providing an important basis for users to establish a visual spatial reference coordinate system. However, because vector data is usually stored in Shape file format, the data structure is irregular and the spatial distribution is not uniform, so it is difficult to simplify the vector data directly by traditional tile layering method. In this paper, the vector data is rasterized first, then stored in the way of image tiles, and the spatial correspondence between vector data and image tiles is established. Then the translucent effect is realized through Alpha channel, so that the multi-layer data can be dynamically overlapped.

### 3.2. Scene Dynamic Rendering

The amount of terrain, image and vector data for building 3D digital earth is very large, so it is impossible to read all the data into memory at one time, but it must be dynamically scheduled between memory and memory according to the continuous transformation of scene view. According to the gradual change of the roamer's viewpoint, the data that will fall into the visual area and is temporarily absent in memory will be read into memory. Because of the limited memory capacity, the memory space occupied by the data, which is temporarily out of view, must be released in time to ensure the balance of the amount of data in memory.
4. Visual Simulation of Scheduling Tasks

4.1. Satellite Model Generation

The 3D geometric model of satellite is generated according to the real size by the modeling tool 3DS Max. At the same time, the local model coordinate system with the platform load as the reference is established to facilitate the manipulation based on celestial coordinate system in orbit attitude control. The schematic diagram is shown in Figure 4. The active components such as satellite platform, solar panel and imaging load are modeled by a single node combination, which supports the internal animation control of the later program running. Three-dimensional model data is stored and loaded in binary file as a whole, and its internal structure is identified and pre-processed when it is first read into memory.

Compared with the earth model generated by dynamic loading of terrain, images and vector data, the internal structure of the satellite model is more complex, considering not only the overall motion of the satellite model, but also the individual motion of solar panels and other components. In addition, unlike the Earth model, in order to make the satellite model look beautiful and realistic, we need to use different materials, textures applied to different parts; of course, the more important thing is to ensure that these settings can be fully reflected in the graphics engine.
4.2. Calculation and Generation of Satellite Orbit

Satellite orbit calculation is the basis of three-dimensional visualization simulation. The six elements of satellite orbit can calculate the position of satellite at any time more accurately, and the influence of Sun-Moon gravitational perturbation, atmospheric drag and earth's oblations can be considered at the same time. The orbital elements mainly include Kepler orbit parameters, such as inclination angle, ascension meridian, perigee angle, orbit semi-major axis, orbit eccentricity and true perigee angle, which can be used to determine the position and velocity of the satellite at any time. In this paper, the simulation engine system is sampled and calculated in 1-second interval, and the visual intermediate state is obtained in real time by smooth interpolation and orbit extrapolation[5].

Because of the perturbation effect, especially the orbit fitting of LEO satellites, it is necessary to consider six orbital parameters and nine perturbation parameters with 15 parameters[6]. In order to determine the functional relationship between satellite position and ephemeris parameters, it is necessary to obtain the partial derivatives of satellite position to 15 orbital elements. For space limitation, only the partial derivatives of the satellite position to the orbital inclination of the reference epoch are listed here. The other derivations are given in the relevant literature.

$$\frac{\partial x}{\partial i_0} = r_k \sin i_k \sin \Omega_k \sin \Omega_k$$

(1)

$$\frac{\partial y}{\partial i_0} = -r_k \sin i_k \cos \Omega_k \sin \Omega_k$$

(2)

$$\frac{\partial z}{\partial i_0} = r_k \cos i_k \sin \Omega_k$$

(3)

Among them, $r_k = |r_k|$ ($r_k$ is the three-dimensional coordinate vector of the satellite position), $i_k$ is the orbit obliquity, $\Omega_k$ is the ascension point meridian, $u_k = \Phi_k + \delta u_k$ and $\Phi_k$ is the ascension distance. The satellite position $r$ can be linearized by calculating the partial derivative of the satellite coordinate to the broadcast ephemeris parameters and neglecting the small amount above the second order.

$$\mathbf{r}_k = \mathbf{r}_0 + \sum_{i=1}^{15} \frac{\partial \mathbf{r}}{\partial \beta_i} \delta \beta_i$$

(4)

Among them, $\beta_i$ (i=1, 2, 3, ..., 15) is broadcast ephemeris parameters, $\mathbf{r}_0$ is the initial coordinate of the satellite.

4.3. Satellite Attitude Control

The key of remote sensing satellite visualization rendering is the dynamic presentation of real-time position and attitude information, especially the satellite load and attitude directly determine the accuracy of its earth observation area. As shown in Figure 4, the point O is the origin of the world coordinate system.
(earth) coordinate system $OXYZ$, $O_s$ is the origin of the satellite local coordinate system $O_sX_sY_sZ_s$, $OO_s$ and is the vertical altitude of the satellite from the center of the earth. If the satellite is placed directly in orbit through translation, its initial attitude is shown in Figure 4, and its three coordinate axes are consistent with the global coordinate system. Therefore, it is necessary to adjust the satellite axis through attitude transformation to ensure that the tangent speed of the satellite axis $X_s$ is consistent with its tangent speed under non-maneuvering condition. In the process of system simulation, it is required that the satellite attitude should be vertical and downward toward the center of the earth in normal state, and the front of the satellite should be in accordance with the tangential direction of the current orbit of the satellite. At the same time, the solar tilt should be parallel to the orbit of the satellite and toward the sun. The flow chart of calculating the default attitude matrix of the satellite is shown in figure 5.

![Flow chart of calculating the default attitude matrix of the satellite](image)

**Figure 5.** Generation process of satellite gesture matrix

The position and attitude of a remote sensing satellite are constantly changing. The target attitude is usually controlled by three Euler (pitch, roll and course) angle parameters in the maneuver phase of a mission, and the intermediate state is automatically interpolated by the simulation system. In addition, the satellite also handles internal motions such as sail opening, steering, and load changes, which need to be demonstrated by event-driven means.

### 4.4. Star Points and Strip Generation

Under satellite point is the intersection of the line between the satellite and the earth's center and the ground. It is the projection of the satellite on the ground. It can be expressed directly by longitude and latitude. The trajectory formed by the continuous movement of the sub satellite point on the earth is called the sub satellite trajectory. Considering the influence of satellite motion and earth rotation, the shape of satellite's sub-satellite point trajectory is different in different orbits. Therefore, sub-satellite point trajectory is an important way to understand and grasp the satellite's operation status and orbit characteristics[2].

It is often used for real-time tracking of satellites, and can assist in monitoring and analyzing the satellite's operation status. In order to verify the feasibility of the imaging mission scheme, the intersection of the satellite's current position with the earth's surface grid is computed in real-time by using the space ray intersection method. The intersection points with continuous intervals are sequentially put on the stack and constructed into a curve to form the sub satellite point trajectory.
Field angle
Satellite swing direction
Scan coverage area

Figure 6. Schematic diagram of scanning strip generation

Scanning strip refers to the ground coverage area formed by the camera load during the satellite movement. Because the angle of view of the camera load observation is generally fixed, the strip width is constant, also known as the amplitude width. Width describes the effective width of surface coverage when remote sensing satellite scanning and imaging to the ground. The acquisition of multi-band mosaic images based on the agile maneuverability of satellites or the realization of wide-area observation in multi-satellite networking mode, are often used by remote sensing satellites, and are one of the main purposes of satellite mission planning. In the simulation system, the ground-scanning strip is generated in real time. Firstly, the intersection point between the load axis and the ground is calculated according to the satellite space-maneuvering attitude. Then, the imaging strip boundary is calculated according to the satellite load imaging angle and the satellite motion direction. On the other hand, the scanning strip width is directly set up, which can be disproportionate by real-time calculation. The feasibility of the imaging task scheduling scheme is often accurately verified.

5. Experimental Verification of Real Data

The simulation system interface is shown in Figure 7. The left window is the key task node distribution represented by tree control. The middle main view is divided into three-dimensional simulation window and two-dimensional display window. The following is the satellite mission/time distribution represented by Gantt graphics.

The bottom layer completes 3D graphics rendering based on the OpenGL interface. A typical case is validated with the mission planning data of a real imaging satellite. Finally, the visualized real-time scene of mission scheduling of imaging satellite with the earth as the center is constructed. A large number of real-time data or original data are calculated and normalized scientifically. It is transformed into graphics, images and interactive animation, which is expressed in a more vivid, intuitive and holistic way.

Figure 7. Operation interface of 3D visual simulation system

The digital earth in this system is an open data source format. The terrain adopts the global 80-meter resolution local 25-meter resolution DEM regular grid digital elevation data. The image adopts
the global 50-meter resolution local high-resolution 0.6-meter resolution image. Based on bilinear interpolation, the LOD pyramid is preprocessed and the finest image is obtained. The data reach 18 levels, all data are layered by TMS tiles and file directory service is established.

![Planning area verification](image1)

![Testing unplanned imaging area](image2)

![Scheduling global and local clients for multiple imaging tasks](image3)

**Figure 8.** Screenshot of 3D visual simulation system

The system runs on the Lenovo T470 notebook with independent graphics cards, which is configured as follows: Windows 764-bit operating system; i5-7200 CPU, dual-core main frequency 2.5GHz; NVIDIA GeForce 940MX graphics card, which supports GPU graphics acceleration; 500GB solid-state high-speed hard disk.

![Variation of frame rate under different conditions](image4)

**Figure 9.** Variation of frame rate under different conditions

The operation effect of the 3D visualization simulation system is shown in Figure 8. In order to test the performance of the algorithm and the overall efficiency of the system, we select the typical frame rate changes of 180 seconds in the two typical stages of "maneuvering imaging" and "multi-strip stitching" respectively when one satellite and three satellites are loaded. Table 1 shows the comparison of average frame rate, maximum frame rate and minimum frame rate under different conditions.

|                      | Maneuver imaging (1 satellite) | Multiple strip splicing (1 satellite) | Maneuver imaging (3 satellites) | Multiple strip splicing (3 satellites) |
|----------------------|-------------------------------|--------------------------------------|---------------------------------|--------------------------------------|
| **AVG fps**          | 52.1931                       | 47.0641                              | 36.6866                         | 32.6170                              |
| **MAX fps**          | 56.9732                       | 54.3126                              | 43.5968                         | 41.6955                              |
| **MIN fps**          | 46.6088                       | 40.4788                              | 28.3081                         | 22.9238                              |

**Table 1.** Frame Rate Comparison of Scene Rendering under Different Conditions.
It is not difficult to see from the diagram that in the two stages of "maneuvering imaging" and "multi-strip splicing", although the system needs to calculate and draw the sub-satellite trajectory and ground stripes in real time. The overall performance of the system is not significantly affected; while the system simulation loads three satellites, although the overall performance of the system is somewhat different, but also meet the minimum 25 fps real-time interactive system frame rate requirements, it can be seen that the system has a very stable rendering efficiency and engineering practicality.

6. Conclusion
Space visualization provides an intuitive expression for spacecraft in-orbit operation, and has been used more and more in spacecraft mission design and planning. In this paper, based on graphics engine and combined with satellite orbit calculation, earth observation and maneuver modeling, the whole process of mission scheduling is fully reproduced. Compared with the traditional visualization application based on SDK, this paper studies the 3D digital earth application as the starting point, which is completely based on the autonomous and controllable 3D graphics engine. Its digital earth loading terrain, image and vector resolution are not limited, and it can realize the seamless transition based on LOD. The dynamic model reproduces the task scheduling process of remote sensing satellite, which is more conducive to the detailed comparison and more accurate to verify the feasibility of the scheduling scheme.

The next step is to standardize the remote sensing satellite simulation control data and motion description to form a protocol standard, and improve the simulation platform to meet the needs of various types of applications in the case of compatible with a variety of mission scheduling planning.

7. References
[1] K. A. Ezzat, L. N. Mahdy, A. E. Hassanien, A. Darwish, Robust Simulation and Visualization of Satellite Orbit Tracking System, International Conference on Advanced Intelligent Systems and Informatics, 2018, pp. 505-514.
[2] Y. Kazansky, D. Wood, J. Sutherlun, The current and potential role of satellite remote sensing in the campaign against malaria [J], Acta Astronautica, 2016, 121:292-305.
[3] Y. Zhang, X. Liu, C. Hao, G. J. J. o. D. Yang, Control, Visualization Methods of Low Orbit Satellites Detecting Time Window[J], 2017.
[4] R. Zhai, K. Lu, W. Pan, S. J. N. Dai, GPU-based real-time terrain rendering[J], 2016, 171(C):1-8.
[5] X. B. Cao, J. X. Zhang, Z. W. J. A. S. S. S. Sun, Digital Platform for Satellite Orbit Design and Mission Analysis[J], 2004.
[6] D. Wei, C. Zhao, an Accuracy Analysis of the SGP4/SDP4 Model [J], Chinese Astronomy & Astrophysics, 2010, 34(1):69-76.