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Lunar Rover Virtual Simulation System with Autonomous Navigation

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***Abstract*—**The paper researched and presented a virtual simulation system based on a full-digital lunar terrain, integrated with kinematics and dynamics module as well as autonomous navigation simulation module. The system simulation models are established. Enabling technologies such as digital lunar surface module, kinematics and dynamics simulation, Autonomous navigation are investigated. A prototype system for lunar rover locomotion simulation is developed based on these technologies. Autonomous navigation is a key technology in lunar rover system, but rarely involved in virtual simulation system. An autonomous navigation simulation module have been integrated in this prototype system, which was proved by the simulation results that the synthetic simulation and visualizing analysis system are established in the system, and the system can provide efficient support for research on the autonomous navigation of lunar rover.

***Keywords*—**Lunar rover, virtual simulation, autonomous navigation, full-digital lunar terrain.

I. INTRODUCTION

THE moon is the nearest celestial body and the only natural satellite of the earth; it also possesses rich resources with broad development prospects. In recent years, there has been a growing interest in navigation of the moon among the nations. China is one of the great powers of aerospace research, and lunar exploration will be the start of its future interplanetary explorations. Lunar rover is a kind of detector which is able to adapt to the different environment of the moon, loaded with scientific detection instruments and transmit the final probe data back to the earth. A detector system requires a large number of tests. Compared with the real ground simulation test, to a large extent, computer simulations with the application of virtual reality technology is a high-efficiency, low-cost way that provides a good means of verification for the detector design and control algorithm optimization.

National Aeronautics and Space Administration (NASA) has been doing a great many researches in lunar rover as well as Mars rover simulation. NASA Jet Propulsion Laboratory (JPL) researched in different types of lunar rover navigation systems [3, 7], and developed a simulation system called ROAMS[2]. Besides, Carnegie Mellon University (CMU) [1] and France LAAS-CNRS have done a lot of work on autonomous navigation system respectively. Autonomous navigation is a key technology in lunar rover system, but rarely involved in virtual simulation system.

This paper mainly researched a virtual simulation system based on a full-digital lunar terrain, integrated with kinematics and dynamics module as well as autonomous navigation module. Chinese scholars researched in lunar rover navigation system and virtual simulation system respectively, but rarely thinking of integrating them together. This paper presented a lunar rover virtual simulation system based on lunar surface geometry and physical properties integrated with autonomous navigation module.

II. THE SYSTEM ARCHITECTURE

The system architecture of lunar rover virtual simulation is illustrated as Fig. 1. First, we have a geometric modeling module which generates both digital moon terrain and digital moon rover. The digital moon terrain plays a crucial role in this system, on which path information is parsed and collision detection is based. As for dynamic, there are three important modules: kinematics, dynamics and motor drive control. Those can provide analysis for rover to navigation while the terrain parameters are needed from path information. In whole, navigation and collision detection is integrated and conducted in the lunar rover simulation platform on virtual environment. Based on the environment, virtual test and validation can be conducted for path planner, which is a core part of discovery mission.

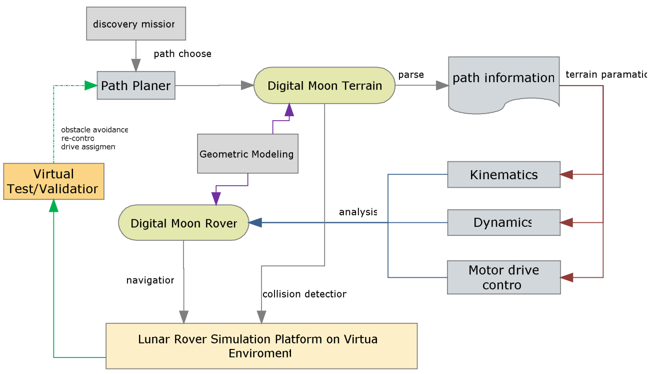

Fig.1 System Architecture

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A. Geometric Modeling

As mentioned before, the products of geometric modeling contains two parts: digital moon terrain and digital moon rover. For digital moon terrain, we also divide it to two portions for generating: terrain surface and moon features models (crater,stone,valley and soil), which are modeled by fBM (Fractional Brownian motion) Diamond-Square algorithm and fractal geometric respectively. Besides, the digital moon rover is modeled by a commercial 3D modeling software.

The digital moon terrain and digital moon rover are integrated into model integration/publish interface for experimental field, simulation analysis and virtual scene. The file format for conversion can be STL, Openflight/PFB and customize format, which is as shown in Fig. 2.

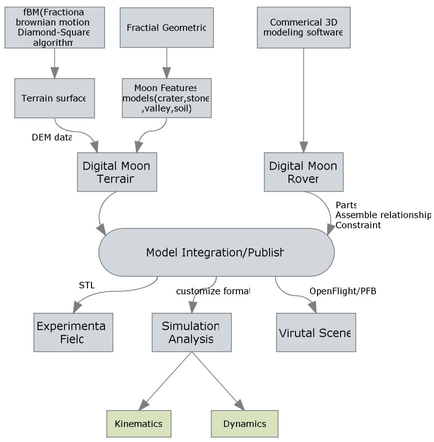


Fig. 2 Geometric Modeling

B. Kinematics and Dynamics

In the traditional understanding, we considered that lunar rover move so slowly that we could ignore the dynamic influence. Additionally, it will waste a lot of computing resource to take dynamics into account. Therefore, most of the similar systems entirely ignored the dynamic influence. However, too many assumptions will eventually lead to the result of "distortion simulation" which makes the less reliability for the lunar rover of the real world. This has been proved by lunar rover single-wheel bench test results. Based on the domestic related papers published, recently many domestic research institutes have been focused on dynamics simulation and its relative domains. We believed that it will take long for comparing the simulation with the test result.

The motion control module in this system using Vortex software to complete the following tasks: the initialization of lunar rover geometric property parameters and physical attributes, the definition and solution of constraints, collision detection and collision response, control signal processing interface. Dynamics module mainly complete with establishing and solving kinetic model, among which the interaction between wheels and lunar soft soil is the focus content.

C. Visualization Module

Visualization module is an interface between simulation system and operators, the main function of which is to import the file of terrain and lunar rover, building up a scene tree, using three-dimensional graphics rendering methods (scene model management, texture mapping, lighting, real-time shadow, three-dimensional text and so on) to display the virtual lunar environment and analyze real-time status of the rover, including 3-D full-digital lunar terrain, dynamic lunar rover and some relative parameters display. First, import lunar rover model and terrain data; convert them into an OpenGL Performer scene graphics. A view into the scene graphics is described by a channel. This view is rendered by an OpenGL Performer software pipeline, then display into a window, on a selected screen. This rendering process is shown in Fig. 3.

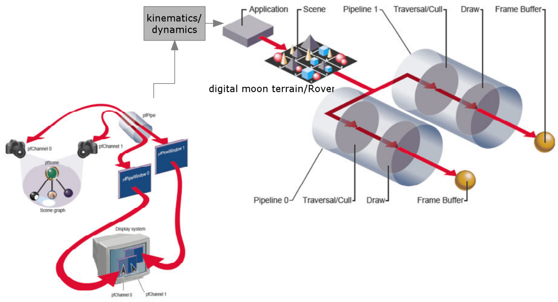


Fig. 3 Visualization module based OpenGL Performer [11]

D. Visual Navigation

This module simulates lunar rover autonomous navigation. It captures the front image of the vehicle in real-time, analyzes the captured image, distinguishes obstacles and make decisions for path planning and autonomous navigation control. There will be frequent interactions between visual navigation modules and other modules, so interface and information exchange work turn out to be very important during integrating process.

III. Key Technologies

A. Full-digital Lunar Terrain

Digital lunar terrain is the basis of virtual simulation. The surface of lunar is the continuous ups and downs of craters and valleys. Therefore, the digital lunar terrain should include these basic elements such as slopes, craters and stones, meanwhile in order to achieve a better simulation result, it should be in accord with the real lunar surface as much as possible. As a natural terrain, the lunar surface has very obvious fractal characteristics. It is reasonable to use the fractal technology to form the lunar base terrain. First it uses the fractal technology to form the lunar base terrain and stone upon the lunar surface, then adds lunar craters and stones to the terrain according to the real statistical data, then joint hill model around it, forming a realistic parameterized virtual lunar surface for lunar rover simulation, as Fig. 4.

In a digital simulation, not only a basic lifelike lunar terrain is necessary, while in an autonomous navigation simulation, the geometric properties and location information are also required, besides, the feature of the terrain in this lunar rover simulation platform needs to be expressed as well. The files of terrain attribute and geometric properties together constitute a complete full-digital lunar terrain. In this paper, we describe geometric properties and position attribute by means of XML. XML (eXtensible Markup Language) is a general-purpose specification for creating custom markup languages, which is a powerful tool to deal with structured documents. XML supports custom tag and provides a powerful expansion mechanism. So XML is very suitable for expression of the attributes of geographic information.

Lunar terrain can be categorized into base terrain, pits, stones, soil properties. First of all, create a terrain tree for lunar terrain, and then describe base terrain, pits, stones, soil properties as branch of the tree respectively.

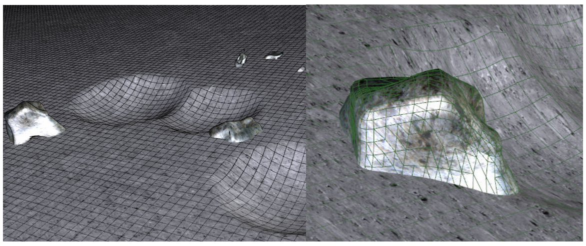


Fig. 4 Lunar digital terrain

B. Dynamic Module

1) Wheel-Terrain Interaction Model

There are already many researches about Wheel-Terrain Interaction Model. However, most of them assumed the interaction is rigid contact which will lead a decrease in accuracy and reliability of lunar rover dynamic analysis. According to the relationship between the rover wheel and terrain, this paper gives an assumption that wheel is rigid while lunar surface is soft and adopts the Bekker pressure and torsion model (see Fig. 5).

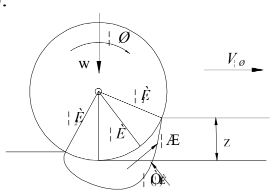


Fig. 5 Rigid Wheel—Lunar Surface Interaction Model

By vertically, rigid wheel's load W passes to lunar oil through interact-face and should be balanced by lunar surface's counter-force. If the stress in the width b of rigid wheel is same, then W can be presented as follow:

$$\mathrm{W} = \mathrm{rb}\left[\int_{\theta_1}^{\theta_2} \sigma(\theta)\cos\theta \mathrm{d}\theta + \int_{\theta_1}^{\theta_2} \tau(\theta)\sin\theta \mathrm{d}\theta\right] \quad (1)$$

b is the width of rigid wheel in the equation above.

The pull force of rigid wheel cruising on soft lunar surface is:

$$F_{DP} = rb\left[\int_{\theta_1}^{\theta_2} \tau(\theta)\cos\theta d\theta - \int_{\theta_1}^{\theta_2} \sigma(\theta)\sin\theta d\theta\right] \quad (2)$$

Wheel distance M_w:

$$M_w = r^2 b\int_{\theta_1}^{\theta_2} \tau(\theta) d\theta \quad (3)$$

2) Real-time Collision Detection

Real-Time collision detection is a basic function of Virtual Reality system. Collision detection of every collision model in the system need to calculate all the geometry relationship with other models while the process of judging the relationship between two facets is complicated and consume much computer resource. Because there are complex models of rover, surface and rocks in virtual environment and a high requirement for real-time and realness, the real-time collision detection technology contributes an important meaning for full virtual environment in this research. The collision model is divided into several different layer structures. The efficiency of collision detection is improved by approach of combination between rough collision and exact collision. The key point of this technology is that $O(N^2)$ times detection for N models, which leads to a high computing complexity when N is big. If we divide the system into several detection spaces, find potential collisions by fast collision among spaces, and then use facet model to conduct accurate collision and get collision information, much time and resource can be saved. Besides, since the collision space can be comprised mutually, different layer structures can be applied to virtual environment to improve speed of collision detection further.

C. Path Planning and Visual Navigation

Lunar rover is usually navigated and controlled by wireless, but sometimes not available because of the change of the relative geometry relationship by rotation and revolution of Earth and lunar. So self-navigation and control by the devices on the lunar rover is an important trend [6,9]. There are a lot of researches about navigation, some of which are integrated in this paper.

Nowadays, the navigation technology includes stereo navigation, sun-sensor and inertia navigation, etc [1,7,10]. Compared to other navigation technology, stereo navigation has big advantages on reliability and information quantity and the development of this field has made the application in real rover more practicable.

In this paper, not only the visual effect is considered in the simulation, but also the process of navigation and algorithm verification is simulated. The navigation simulation contains three parts: image acquisition, image process and path planning and navigation. Image acquisition module gets the surface image in front of rover by virtual CCD camera. The image is processed by image process module by querying digital terrain and getting the altitude and obstacle information. The last module is responsible for path planning and control the rover to avoid obstacles by relevant algorithm.

1. Image acquisition

In real system, the rover navigation system gets the image ahead by CCD camera fixed in rover. To achieve the realness in laws of physics, we use the same image-acquisition principle to get image in virtual simulation system. First, a pair of cameras is added on the rover model, which is visible in virtual scene. The cameras are taken as a viewpoint locked in rover in simulation system. The rover get the geometry and location information of the viewpoint by dynamic module's calculation: location coordinate(x,y,z) and posture matrix. Then we get the relative geometry relationship between camera and digital terrain. So the range of terrain and image in the viewing volume can be acquired based on the principle of camera and terrain information. The image (RGB format) is saved in system and can be provided for visualization module and image processing.

2. Image process

After the surface image and terrain range, we can use the XML properties file of digital terrain to query information about obstacles, which includes obstacle types (rock, hole and slope), position (x,y,z) and size (altitude, diameter and cover area). That information is all recorded in a single XML file as the obstacle information file. The system can provide information service for subsequent module.

3. Path planning and control

When the path planning and control module get the obstacle information, the system firstly list some potential path and evaluate all the steering-ability by the obstacle information in every path. The criteria of evaluation are shown in Table I. The path which has the highest steering-ability will be chosen as ultimate path. Then system send instructions (keep same direction, change direction or turn back) to motion control module to keep rover going or turning. Simultaneously, the direction is shown in the visualization module.

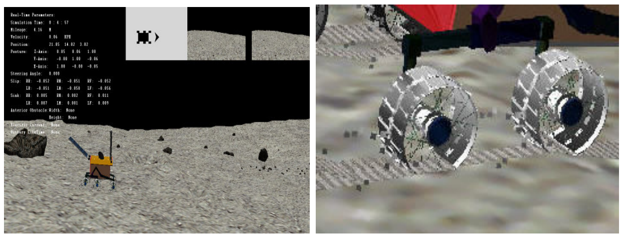
TABLE I
CRITERIA OF EVALUATION

Type	By-pass/Cross	Standard
bulge	By-pass	gradient>30o
bulge	Cross	gradient :15 o ~30o
dent	By-pass	depth :0.25 ~ 0.4m
dent	Cross	depth :0.1 ~ 0.25m
obstacle	By-pass	altitude>25cm
obstacle	Cross	altitude <25cm

IV. PROTOTYPE SYSTEM AND ITS APPLICATION

The prototype system is developed on a SGI ONYX 350 super-computer, three BARCO projectors and FOB, Data Glove, Stereo CrystalEye, etc.

The simulation interface of rover cruising in lunar surface is shown in Fig. 6. By keyboard input we can control the rover forward, backward, turn left or right. The pan and rotation can be completed by mouse click. So the operator can observe the real-time position and gesture of rover by multi-angle. The two small windows in the Fig.6 (a) is the real-time image by two cameras in rover while texture in left side shows the real-time parameters. The rover can realize autonomous navigation by analysis of image and parameters.



(a) Simulation interfaces (b) Track effect

Fig. 6 Interface of simulation system

V. CONCLUSION

This paper mainly present a lunar rover simulation system integrated with dynamic and visual navigation. First, a full digital complex lunar terrain with properties based on XML file is established by fractal technology and statistical regularity. Then we research and set up the wheel-soft-terrain interaction model and develop a prototype simulation system. The follow-up work is expected to generate a digital terrain which is the same with real experimental terrain so we can conduct comparison between real test data and simulation data. Besides, since there is high requirement in computing ability for 3D rendering and image processing, to develop a High-Performance-Computing (HPC) system to support simulation system is another research field.

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