Vision Guided Modeling and Simulation for CAS Rover

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***Abstract*—With the potential application of planetary exploration, the issues on vision-guided modeling and movement simulation technologies for the planetary rover of Chinese Academy of Sciences (CAS) are investigated. Based on stereo vision and the virtual reality, a simulation platform is developed. The system working in an off-line teaching way can be used to ensure the safety of the rover. Firstly, a detail description of the CAS rover mechanism structure and kinematics model is given. Secondly, the implementation process of simulation platform based on OpenGL has been introduced. Finally, movement simulation on synthesis terrain and real terrain got by stereo vision are executed, and the simulation results show the validity of the whole scheme, and the scheme has the availability for future exploration operation.**

***Index Terms*—Planetary rover, Kinematics model, Stereo vision, Virtual reality**

I. INTRODUCTION

Planetary Rover Technology is a comprehensive interdisciplinary technology, which reflects a whole national science and technology level and development level of high technology industries. It has far-reaching sense for studying Planetary Rover[1]. In the world, there are a large number of scientific powers which attach great importance to the research of Planetary Rove r and have made great achievements. American Rocky 1~9 series Planetary Rovers, which are the prototypes of the most follow-up Mars rover, are developed by jet propulsion laboratory (JPL)[2]. They are mainly used for doing experiment of a long distance autonomous navigation and control on the ground. Meanwhile, a reliable rocker-bogie mechanism is proved, which is widely used by follow-up rovers. Ranger is developed by Carnegie Mellon University and its functions of binocular stereo vision system and the positioning accuracy were tested at Art Kama desert in Chile in 1997[3]. "Sojourner" is developed based on the Rocky series Planetary Rovers. It was equipped with panoramic cameras and stereo binocular vision system and sent to Mars surface for three-month's scientific investigation in July, 1997[4,5]. "Opportunity" and "Spirit" arrived at Mars in early 2004, which have returned a lot of precious data and found evidences of once existed water on the Mars. So far, they still carry on scientific investigation on Mars. The whole motion planning is completed in the ground control station and the images are processed after returned. With the virtual reality technology, autonomy and remote control of Mars Rover are combined [6].

In summary, Planetary Rover works in special environment generally. According to the power consumption and payload and other problems, it is obvious that stereo vision localization based on visual sensor is the first choice for all kinds of Planetary Rover to perceive environment [7]. Virtual reality technology, also called LingJing technology, uses computer to generate 3D dynamic graphics and make the operator have the feeling that be personally on the scene through the sight, hearing and touch. It has three features including immersion, interaction and conception. Ground human-computer interaction system can be built based on the stereo vision technology and virtual reality technology [8-11]. This system has the function of off-line teaching. Through the stereo vision technology and virtual reality technology, the virtual rover can move on virtual terrain and the virtual manipulator can grind virtual object. The operator will upload the data to real rover to realize the true roam and investigation after test various motions of Moon Rover in virtual environment [12, 13]. In this paper, for CAS rover, the stereo vision technology and virtual reality technology are used to build a interactive simulation system which provides a visual and pleasant remote operation environment to operator. Then, motion simulation experiments are taken, which is about virtual rover's movements on synthetic terrain and real terrain. The results show that the scheme has feasibility.

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II. CAR-BODY KINEMATIC MODELING

The basic structure of WMR is shown in Fig.1. It consists of two rocker-bogie which are put on symmetrical positions. The either end of rocker connect front wheel respectively and bogie and the either end of bogie connect middle wheel and back wheel respectively. The two rockers connects car-body via transverse axle [12-14].

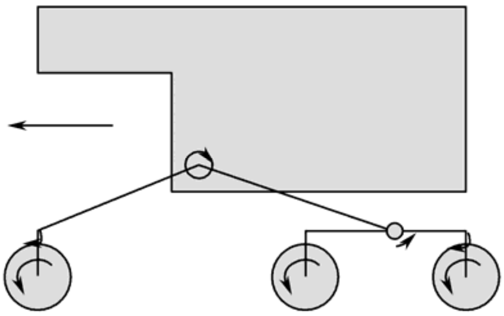


Figure 1. The basic structure of WMR

Just look the definition of right coordinate system of CAS rover as an example. The specific details are shown in Fig.2. The wheels are numbered as 1, 2 and 3 from front to back by right coordinate system. The left coordinate system number the corresponding wheels as 4, 5 and 6. The meanings of all coordinate systems are as follows.

R: Coordinate system of car-body.

D: Coordinate systems of differential hinge center.

B_1, B_2: Coordinate systems of right and left vice rockers .

X_1: Transitional coordinate system of the middle wheel.

A_i: Core wheel coordinate systems of each wheel.

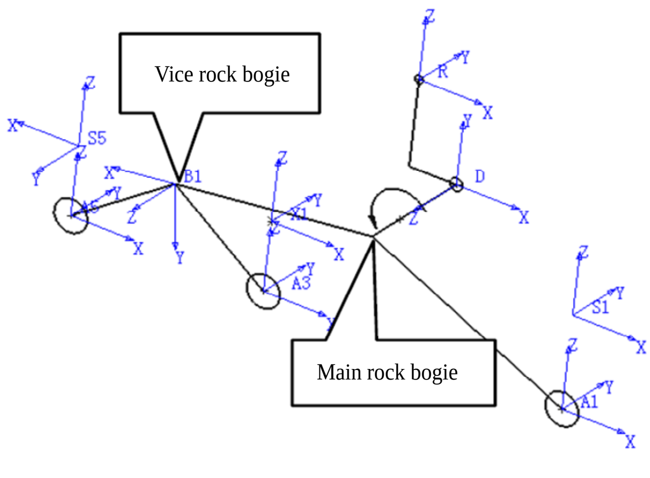


Figure 2. Right coordinate system of CAS rover

The rotation angel between right cradle and Z axis of D is β. According to principle of differential device, the rotation angel of left rocker is -β. The rotation angels ρ_1 and ρ_2 are generated by bogie which respectively rotates with Z axis of B_1 and Z axis of B_2. The e rotation angels of steering wheel are defined asψ_1, ψ_2, ψ_3, ψ_4.

On the basis of the method of D-H coordinate transformation, a series of coordinate systems are established to show the relation of move and rotation between each motion joint of robot in references [15, 16]. As shown in Table 1, status of car-body is determined by earth point. So the relations between car-body coordinate system and earth point coordinate systems of wheels are important.

TABLE I.

PARAMETERS of D-H

	θ (rad)	d	a	α (degree)
Ream center	0	-d1	a1	90
Front-right rudder	β	d2	a2	-90
A_1	ψ_1	-d3	0	0
Right Bogie	187.1/180* $\pi + \beta$	d2	a3	0
X_1	172.9/180* $\pi + \rho_1$	0	a4	-90
A_2	0	-d4	0	0
Rear-right rudder	-7.1/180* $\pi + \rho_1$	0	a4	90
A_3	$\pi + \psi_3$	-d4	0	0
Front-left rudder	$-\beta$	-d2	a2	-90
A_4	ψ_4	-d3	0	0
Left Bogie	187.1/180* $\pi - \beta$	-d2	a3	0
X_2	172.9/180* $\pi + \rho_2$	0	a4	-90
A_5	0	-d4	0	0
Rear-left rudder	-7.1/180* $\pi + \rho_2$	0	a4	90
A_6	$\pi + \psi_6$	-d4	0	0

Core wheel coordinate systems A_i can be fixed on the central axis. Considering the interaction between wheel movement and geometrical topology of terrain, the coordinate system of contact point of wheel is defined as C_i. Suppose the contact between wheel and ground is rigid contact and contact form become point in cross section. The contact point should on the extension cord of back-up arm of wheel. The coordinate system C_i is shown in Fig.3. Among Fig.3, terrain angle is defined as δ_i, Z axis of C_i is vertical to the contact surface. The direction of X axis is same with direction of tangential line. Direction of motion is the direction of X axis of A_i. If slipping of wheel is not be considered, each wheel's Jacobi matrix can be deduced.

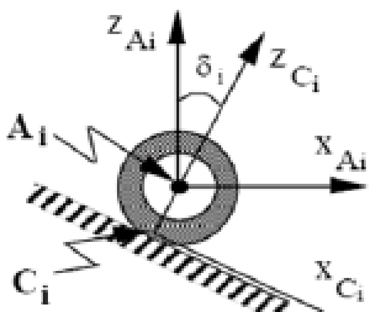


Figure 3. Coordinate system of core wheel and coordinate system of contact point

Through analyzing the Jacobi matrix of wheel and combine with fast projection method, kinematic formula of wheeled mobile robot can be got. Set wheel 3 as an example.

$$\begin{bmatrix}\dot{X}\\ \dot{Y}\\ \dot{Z}\end{bmatrix}+\begin{bmatrix}0 & -K_1 & d_2\\ K_1 & 0 & K_2\\ -d_2 & -K_2 & 0\end{bmatrix}\cdot\begin{bmatrix}\dot{\phi}_x\\ \dot{\phi}_y\\ \dot{\phi}_z\end{bmatrix}+\begin{bmatrix}K_1\\ 0\\ K_2\end{bmatrix}\dot{\beta}+\begin{bmatrix}d_4\cdot c(\beta+\rho_1)+a_4\cdot s(\beta+\rho_1)\\ 0\\ d_4\cdot s(\beta+\rho_1)-a_4\cdot c(\beta+\rho_1)\end{bmatrix}\dot{\rho}_1=\begin{bmatrix}J_{18}\\ J_{28}\\ J_{38}\end{bmatrix}\cdot R\cdot\dot{\theta}_5 \quad (1)$$

In the formula,

$$K_1=a_3\cdot s(W-\beta)-d_4\cdot c(\beta+\rho_1)-a_4\cdot s(\beta+\rho_1)$$

$$K_2=a_3\cdot c(W-\beta)-d_4\cdot s(\beta+\rho_1)+a_4\cdot c(\beta+\rho_1)$$

According to the Jacobi matrices of wheel 1 and wheel 2, formula (2) and (3) can be deduced.

$$\begin{bmatrix}\dot{X}\\ \dot{Y}\\ \dot{Z}\end{bmatrix}+\begin{bmatrix}0 & -K_1 & d_2\\ K_1 & 0 & K_2\\ -d_2 & -K_2 & 0\end{bmatrix}\cdot\begin{bmatrix}\dot{\phi}_x\\ \dot{\phi}_y\\ \dot{\phi}_z\end{bmatrix}+\begin{bmatrix}K_1\\ 0\\ K_2\end{bmatrix}\dot{\beta}+\begin{bmatrix}0\\ 0\\ 0\end{bmatrix}\dot{\rho}_1=\begin{bmatrix}J_{17}\\ J_{27}\\ J_{37}\end{bmatrix}\cdot R\cdot\dot{\theta}_1 \quad (2)$$

$$\begin{bmatrix}\dot{X}\\ \dot{Y}\\ \dot{Z}\end{bmatrix}+\begin{bmatrix}0 & -K_1 & d_2\\ K_1 & 0 & K_2\\ -d_2 & -K_2 & 0\end{bmatrix}\cdot\begin{bmatrix}\dot{\phi}_x\\ \dot{\phi}_y\\ \dot{\phi}_z\end{bmatrix}+\begin{bmatrix}K_1\\ 0\\ K_2\end{bmatrix}\dot{\beta}+\begin{bmatrix}d_4c(\beta+\rho_1)-a_4s(\beta+\rho_1)\\ 0\\ d_4c(\beta+\rho_1)+a_4s(\beta+\rho_1)\end{bmatrix}\cdot\dot{\rho}_1=\begin{bmatrix}J_{17}\\ 0\\ J_{37}\end{bmatrix}\cdot R\cdot\dot{\theta}_2 \quad (3)$$

The new form of kinematic model can be got according to formula (1), (2) and (3).

$$\dot{V}+D_{1i}\dot{\Phi}+D_{1i}\dot{\beta}+D_{2i}\dot{\rho}=M_iR\dot{\theta}_i \quad (4)$$

In the formula,

$$\dot{V}=\begin{bmatrix}\dot{X}\\ \dot{Y}\\ \dot{Z}\end{bmatrix};D_{1i}=\begin{bmatrix}0 & -d_5 & b_i\cdot d_2\\ d_5 & 0 & d_6\\ -b_i\cdot d_2 & -d_6 & 0\end{bmatrix};\dot{\Phi}=\begin{bmatrix}\dot{\phi}_x\\ \dot{\phi}_y\\ \dot{\phi}_z\end{bmatrix};\dot{\beta}=\begin{bmatrix}0\\ \mp b_i\cdot\dot{\beta}\\ 0\end{bmatrix},$$

$$D_{2i}=\begin{bmatrix}d_7\\ 0\\ d_8\end{bmatrix}=\begin{bmatrix}-T_{12}-K_1\\ 0\\ -T_{32}-K_2\end{bmatrix}(d_5=K_1,d_6=K_2,b_i=(-1)^{i-1},i=1,2,\cdots,6)$$

$$M_i=\begin{bmatrix}m_1\\ m_2\\ m_3\end{bmatrix}=\begin{bmatrix}J_{17}\\ J_{27}\\ J_{37}\end{bmatrix}(i=1,2,4,5),M_i=\begin{bmatrix}m_1\\ m_2\\ m_3\end{bmatrix}=\begin{bmatrix}J_{18}\\ J_{28}\\ J_{38}\end{bmatrix}(i=3,6).$$

$\dot{V}$ is the linear velocity vector of car-body. $\dot{\Phi}$ is the rotation velocity vector. Similarly, other models of wheels can be deduced.

III. Motion Simulation Platform of Rover Based on Stereo Vision

Normal work process of teleoperation system of rover is as follows. To begin with, the images of robot's position are taken by the equipped camera. Then, these images and robot's status should be set to control center and transponded to teleoperation system. This system use 3D reconstruction technology to create environment model which would be put into virtual robot that have same geometric model and kinematic model with real robot. Combined with scientific tasks, the operator would plan and test track repeatedly. The completed track information will be set to control center and transponded to robot to be carried out [17, 18]. In this section, based on kinematic model of CAS rover, a visual and pleasant teleoperation environment can be established by the stereo vision technology and virtual reality technology. The simulation results based on synthetic terrain and real terrain shows that this scheme is available.

The whole simulation platform is mainly depended on stereo vision technology and figure simulation technology. The shows of virtual object reconstruction and virtual robot are accomplished in the same window. Firstly, do 3D reconstruction about the collected front terrain. Secondly, start the simulation function of virtual robot. According to 3D coordinates and normal vector of contact points, solution of inverse kinematics of car-body can be done. Last, in order to demonstrate the whole process of motions on various grounds, car-body parts should be refreshed on real-time display according to each joint angle of car-body. Besides, to ensure the safety of robot, the operator would upload relevant data to real mobile robot after simulation validation. The flow chart of whole simulation system is shown in Figure.4.

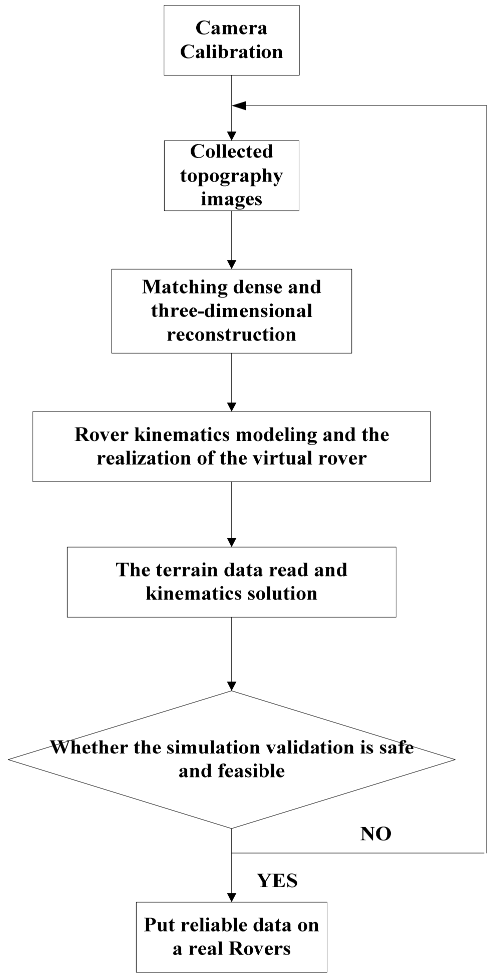


Figure 4. Flow chart of simulation system

Structure of two-tier and three-terminal will be taken in simulation system, as figure5 shows. The virtual layer and real layer are the two layers. The graphics workstation is in the middle side, the operator side is in the left side and the robot the same as planet car side is in the right side. Description of the entire task, the monitoring training of operator, the virtual robot (planet cars), path planning, simulation and kinematics model of the planet car are included in virtual layer. The core algorithm of the whole system, such as technology of binocular stereo vision, technology of virtual reality, rock identification, segmentation and shadow elimination and technology of assessment of three-dimensional surface is included in monitoring the training sessions. Parameter verified is uploaded to true planet car after the task of ideal state is completed by repeated interaction with the interactive simulation system to virtual the movement of planet car in a virtual environment when the mission objectives and the initial state of the system is finalized by operator.

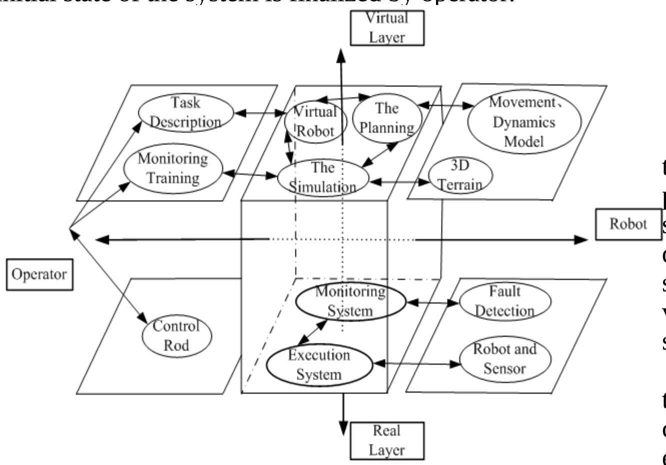


Figure 5. The diagram of all levels consisted in simulation system

Camera, graphics workstations and projection system are contained in hardware part of the system. Image data down streamed from board computer is simulated by pictures collected from two CCD cameras. The reproduction function of the lunar surface images and virtual environments is achieved by image processing, camera calibration, visual computing and 3D visualization software and three-dimensional appearance of the environment is reconstructed by three-dimensional visual software of graphics workstation. Path planning of planet car and manipulator in virtual environment is completed to ensure the safety of the planet car by mouse or keyboard used by operator based on visual interface provided by graphics workstations. This route one of the most feasible and effective options currently is inspected by the actual rover.

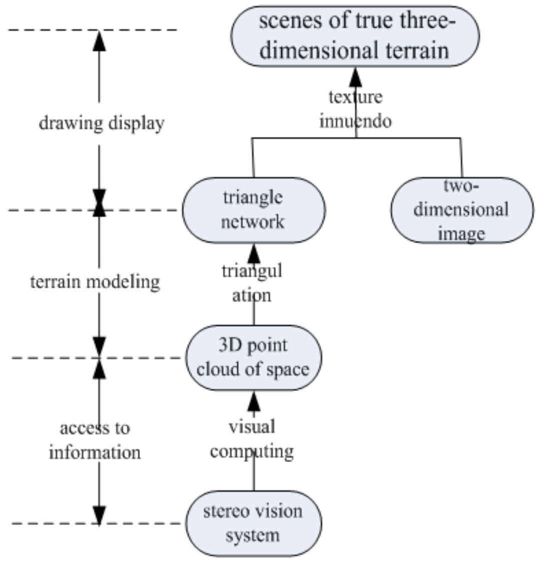


Figure 6. Flowchart of terrain visualization

The original data of terrain is composted by a series of （X,Y,Z(X,Y)） and elevation Z(X, Y) is the function of the plane coordinates (X, Y) and the initial data points are partitioned into triangles grid to represent the terrain surface. Several uneven terrains, such as surface of the downhill, surface of the small barriers, the sinusoidal surface and 3D real terrain reconstructed based on stereo vision can be drawn by the simulation system and the specific is shown in Figure 6.

Models are connected as a tree when each part of the three-dimensional model is moved or moved combinational in control and wheeled mobile robot and each node can be defined as a movement joints graded which can drive next class node. Separate movement or whole movement of virtual environment and objects in the environment can be controlled by programs under the tree structure. Firstly, model of car body is drawn in the program and the model matrix of the body (position and orientation matrix) is put into the stack. Secondly, the mast is drawn and stacked after model matrix of mask is got from model transform. Then, the rocker arm and arm are drawn one by one when the current matrix is the model matrix of the body.

State parameters of the CAS rover are determined by the position and orientation of wheel on the terrain during the simulation. The interaction between rover and the terrain can be modeled as a series of precise collision between wheel and triangular patches of topography. The geometry and topology information of triangular facets is only considered, while physical material properties of the terrain such as friction of static and dynamic coefficient is ignored without considering the model of collision dynamics. The flowchart of simulation is shown in Figure 7.

The true 3D environment terrain is restructured by dense matching of stereo vision system and path planning and initial posture is given to robot priory. The next step of robot is predicted to determine the variation of the terrain angle as the input of the solution to movement learning and the parameters of position and orientation are obtained by inverse kinematics and link of points accumulate. Results obtained by integral are directly used in the 3D display based solely on the kinematics model usually, but optimize the link of value shown in the dashed box is added into the middle to eliminate the various previous errors and optimized results are used in the 3D display. The error can not be accumulated because each cycle will be optimized once [14].

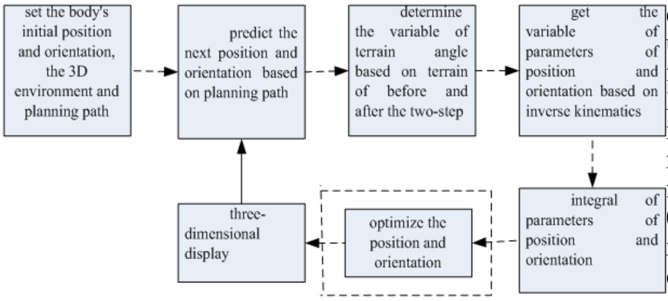


Figure 7. Flowchart of Interactive Simulation

IV. RESULTS OF SIMULATION

The composition of the CAS rover is shown in Figure 8. Two sets of three-dimensional visual positioning system are installed in planet car. The three-dimensional information of the surrounding environment provided for body motion planning is got from the navigation camera on the mast. Obstacles can be circumvented at real-time and three-dimensional information of the surface of subjects being grinded is provided for manipulator of vehicle to guide the robotic arm for positioning and grinding work by avoidance crisis camera in front of the planet car. The same three-dimensional vision software is used in the two cameras. The left image of the experimental terrain is shown in Figure 9.

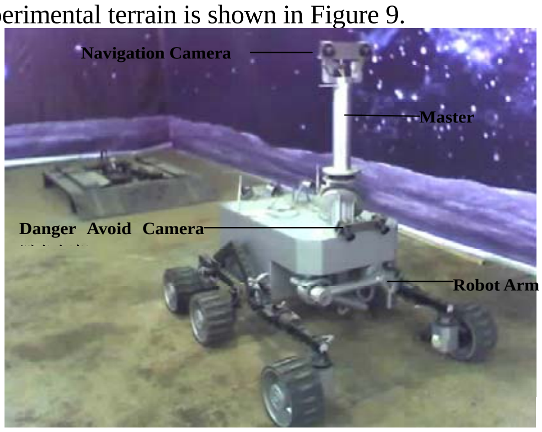


Figure 8. CAS rover

Figure 9. The left image of the experimental terrain

State parameters of the WMR are saved at real-time. Trajectory curve equation of the left wheel is 20*sin(3.14*x/200) and the right one is 20*sin(3.14*x/180) in the virtual tour system. WMR is assumed as linear motion at constant speed of 2cm/s in the simulation. The variation of tilt angle φ_y and roll angle φ_x of the body is described in Figure 10, the left front wheel begins to uphill when the body center Rover X = 222 and the right front wheel begins to uphill when the body center Rover X = 237. φ_y changes from 0 to a negative value, firstly increases and then decreases. φ_y is 0 when the body center reaches the highest point. φ_y changes to a positive value, firstly increases ,then decreases and eventually tends to 0.The change of surface tangent reflected by change of φ_y is confirmed by the variation of curve of φ_y. The change of roll angle φ_x is caused by the difference of the terrain contacted with the left and right wheel. Finally φ_x and φ_y are close to 0 because the body goes back to the initial state and moves in the plane.

Changes of each joint angle of WMR are described in Figure 11, including the cradle corner β and bogie angle (ρ_1, ρ_2). β, ρ_1 mutations and ρ_2 changes lately when the left front wheel uphill. Magnitude of β is smaller than the magnitude of (ρ_1, ρ_2) because length of cradle is greater than the length of bogie.

Variation of contact angle between wheel and terrain is described in Figure 12.The terrain angle mutations and changes as the terrain changes when the wheels start to uphill.

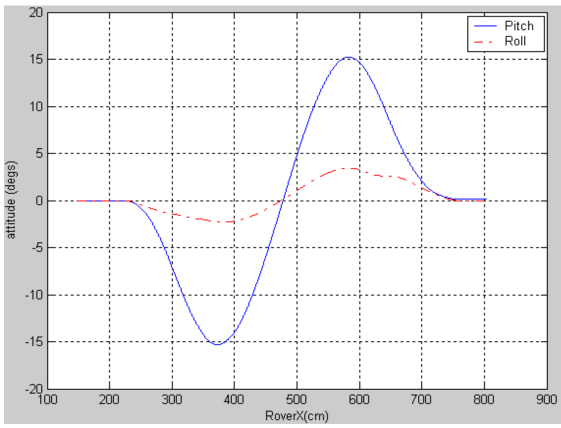


Figure 10. Tilt and scroll of CAS rover

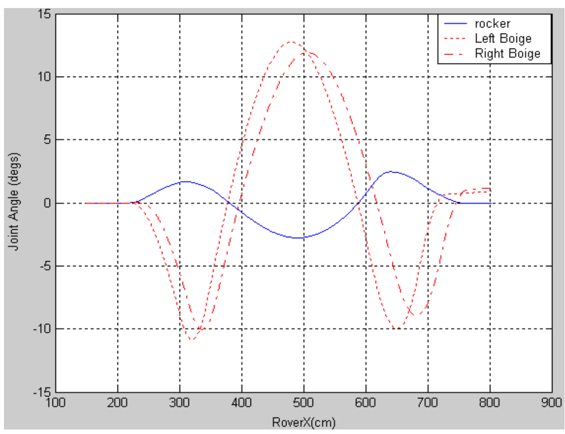


Figure 11. Corner of cradle and bogie

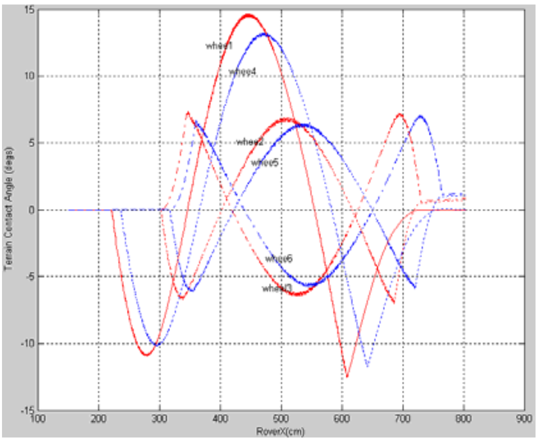
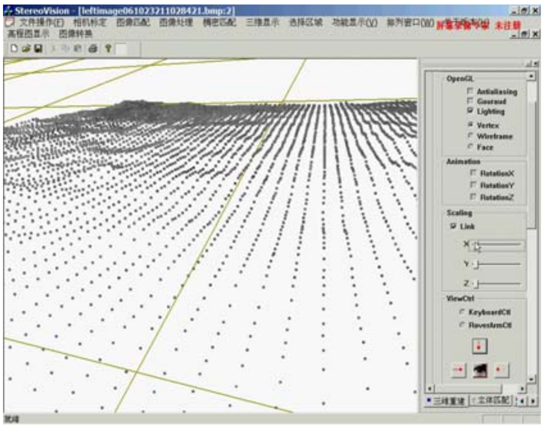
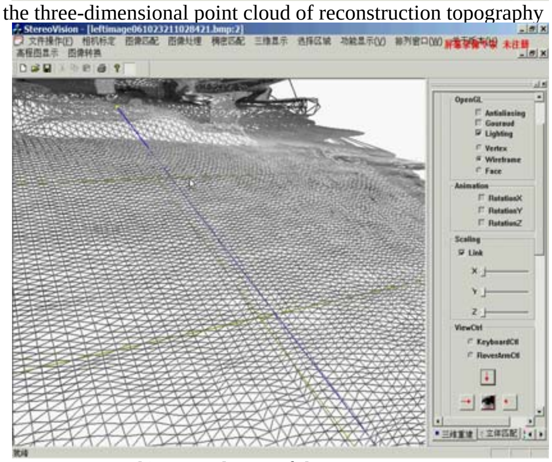


Figure 12. Contact angle between wheel and terrains

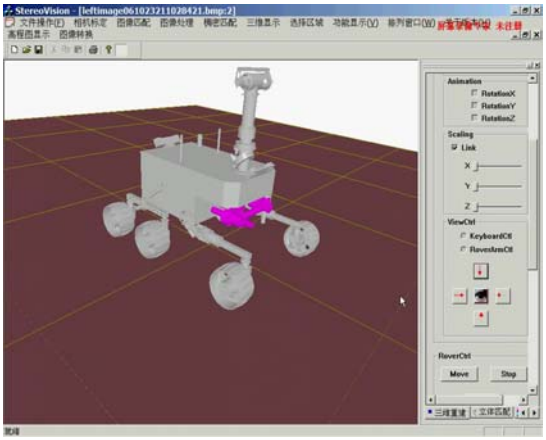
Pathway of 6m x 3m is set in the environment manually and experimental environment is indoor plain of 15m × 20m covered with the gravel. Firstly, environmental images are collected by binocular cameras on the mast and images captured by the left camera are shown in Figure 9. Virtual terrain shown in Figure 13 is formed by the triangulation and texture paste based on the 3D point cloud data of the terrain got by dense matching algorithm. Then, the planning path selected interactively in a virtual environment is certificated virtually by the aforementioned method. Finally, the body should be checked to ensure whether there is danger in the walking process repeatedly until the planning path is all right.



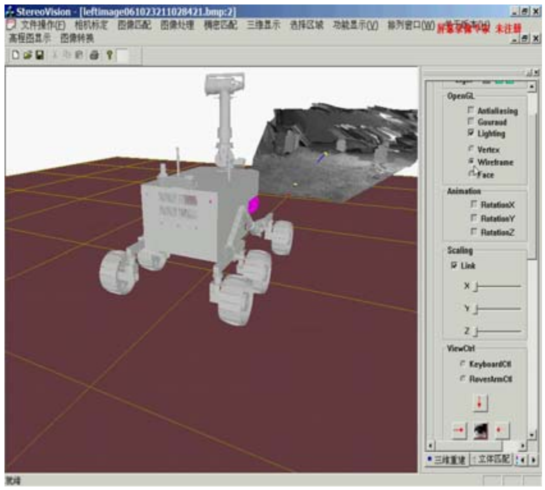
(a) the three-dimensional point cloud of reconstruction topography



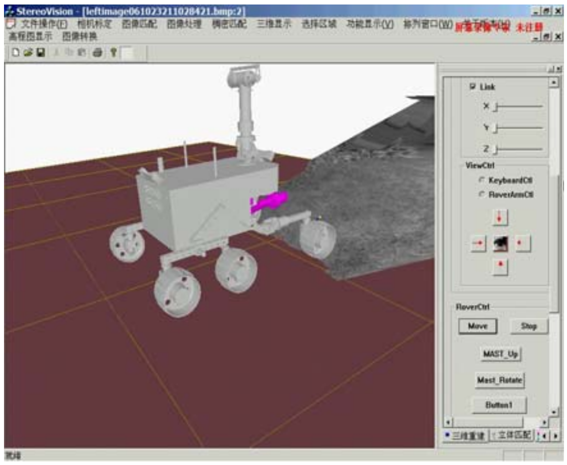
(b) triangulation of the terrain



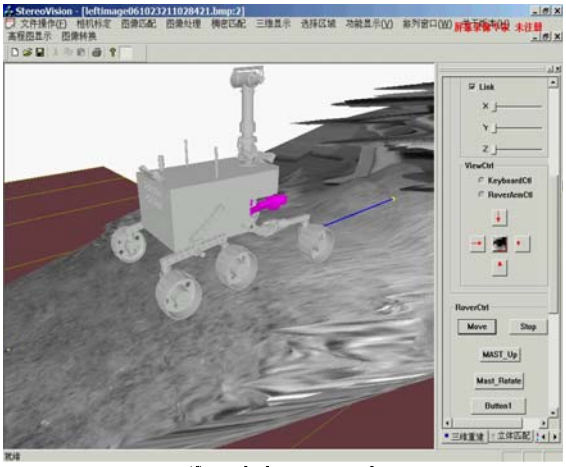
(c) virtual rover



(d) close to the terrain of the rover



(e) rover contacting with terrain



(f) track the given path

Figure 13. Virtual terrain and virtual movement simulation

V. CONCLUSION

A human-computer interaction and simulation system is achieved by virtual reality technology and stereo vision technology according to rover developed by CAS. Kinematics modeling process and the theory of simulation system of CAS rover is described in detail. Real-time status curve of movement on the cross-Sine Surface is analyzed and the correctness of the kinematics model is verified in the simulation of synthetic terrain based on simulation platform built by virtual reality technology and stereo vision technology. In addition, real uneven 3D terrain collected based on stereo vision is simulated and simulation results prove the feasibility of the whole program. The results are significant in the virtual navigation of planetary rover, real-time collision avoidance and teleportation.

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