Design of Comprehensive High-fidelity/High-speed Virtual Simulation System for Lunar Rover

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***Abstract*—Virtual simulation is of great importance for both the research and development phase and the tele-operation phase of a lunar rover. The role and state-of-the-art of rover's simulation is introduced in the beginning. Comprehensive high-fidelity/high-speed virtual simulation system for lunar rover is designed in accordance with the developing trend. Key technologies such as terramechanics and recursive dynamics are discussed and related work that have been done in RCMAC of Harbin Institute of Technology are presented. The system can be switched between high-fidelity simulation and high-speed precision simulation to be used in both phases of a lunar rover.**

Keywords—Comprehensive simulation system, high-fidelity /high-speed simulation, lunar rover, terramechanics, recursive dynamics

I. INTRODUCTION

From the end of the last century, the second lunar exploration upsurge was set off in the world. Many countries and organizations, such as the United States, the European Space Agency (ESA), Japan, China and India, worked out their lunar probing plans. The Spirit and Opportunity rovers have played important roles in NASA's Mars Exploration Rovers (MER) mission, showing the effectiveness of unmanned mobile robots in planetary exploration projects [1]. Lunar rovers are also expected to realize advanced scientific tasks by traveling long distance in the rough deformable terrains (such as craters and rills) in the upcoming activities for exploring the moon.

Literatures on the research of lunar rovers and the successful Mars rovers show that virtual simulation has been playing important roles for both the research and development (R&D) phase and the tele-operation phase of a rover. General simulation tools such as Automatic Dynamic Analysis of Mechanical System (ADAMS), Open Dynamics Engine (ODE), Matlab are used for rover design, evaluation, optimization and control algorithm research by simulation of kinematics [2][3], dynamics [4][5][6], control [7][8][9], and so on.

However, the general simulation tools have limitations. Some rover simulation systems have been developed to meet special demands with high-fidelity, such as American Rover Analysis, Modeling and Simulation (ROAMS) [10][11][12] developed by Jet Propulsion Laboratory (JPL) and European Rover Chassis Evaluation Tool (RCET) [13]. Comprehensive rover simulation tool which combines the modeling, kinematics, dynamics, control and visualization of a rover such as ROAMS is very useful. The current available simulation systems are mainly developed for Mars rovers. Lunar rover's successive tele-operation based on 3D predictive display requires real-time simulation with high speed. Real-time simulation for Mars rover is needless because it cannot take continuous tele-operation mode due to the large time delay. So that comprehensive virtual simulation system that can switch between high-fidelity and high-speed simulation for lunar rover is necessary to be developed.

This paper begins with an overview of lunar rover simulation system from the aspects of its significance and current state. Then the architecture of comprehensive high-fidelity/ high-speed virtual simulation system is designed in accordance with the developing trend. Finally, the key technologies and some related work that have been done in Research Center of Aerospace Mechanism and Control (RCAMC), Chinese State National Key Laboratory of Robotics and System of Harbin Institute of Technology (HIT) are presented.

II. THE ROLE OF VIRTUAL SIMULATION FOR LUNAR ROVER

Virtual simulation can guarantee the success of a rover vehicle for exploring the moon. It is of great importance to a lunar rover from three aspects.

A. Platform for rover design, evaluation, test and control

During the R&D phase of a rover, virtual simulation can be used for configuration design, evaluation and optimization, mobility performance analysis, control strategy research, etc. before a rover was manufactured. For example, before the Mars Pathfinder probe was launched, researchers of JPL predicted that it would turnover while landing because of the interaction between breaking rocket and Mars wind with the help of virtual simulation technology. The technical programme was revised to solve the problem, ensuring the success of soft landing on Mars [14]. To support the study of Mars rovers, the United States developed a comprehensive simulation system ROAMS. Europe is committed to the development of simulation tools RCET, RPET and RCAST for Mars rover evaluation and optimization. Academician Ye Peijian, the general director and general designer of Chinese Chang'e-1 satellite, advocate numerical simulation technology to study the mobility performance of lunar rovers and simulate the floating lunar dust [15]. Beijing Institute of Control Engineering (502 Institute of Chinese Academy of Space Technology) discussed the technical scheme for researching lunar rovers and it is pointed out that a virtual simulation system has the ability of modeling, dynamics simulation, and control simulation should be developed to test the configuration and dynamics parameters of a rover, as well as the control algorithms [16].

B. *Supporting 3D predictive display for successive tele-operation mode*

Exploration activities and moving path of a rover are quite different due to the great uncertainty of planet's surface environment. Therefore, even the most advanced rovers at present, Spirit and Opportunity, do not take completely autonomous control strategy, but be tele-operated by scientists on the earth. Because of the long distance from the earth to the moon and limitation of bandwidth, the time delay of transmission is about several seconds, which makes continuous closed-loop control unstable. This problem can be solved effectively by successive remote operation based on 3D predictive display. Researchers of Japan's Meiji University and Chinese Jilin University, etc. have studied on it [17][18][19]. The ground computers construct virtual simulation environment according to rover status and imagery information of terrain that the rover will move on after the time delay. Operators control the rover in virtual environment and the same commands will be sent to the real rover after error compensation. The real rover will repeat the motion of the virtual one after a while. If the time of sending commands is regulated well, the rover can move successively without stopping.

C. *Validating commands sequence for supervision tele-operation mode*

As transmission time delay from the Earth to the Mars is tens of minutes, supervised tele-operation method is adopted to control Mars rovers instead of the infeasible continuous tele-operation. Researchers from JPL learned an important lesson from Mars Pathfinder mission that a fast, accurate and powerful tool for driving the rover is necessary [20]. So that Rover Sequencing and Visualization Program (RSVP) is developed for rover driving [21]. It is a suite consisting of two main components: ROSE (Rover Sequence Editor) and Hyperdrive. Hyperdrive is an immersive 3D simulation of the rover and its environment that enables operators to construct detailed rover motions and verify their safety. It uses the state information of a rover to analyze and review the current state, identify any anomalous issues, review previously commanded activities and verify that the commanded activities are finished. Scientists define science activities and plan rover’s path with the 3D terrain models built according to the images obtained by stereo cameras. Then the command sequences are built. Sequence validation will be done by simulation and the verified sequence will be sent to the real rover for the exploration of a sol day. RSVP is used for the final generation of command sequences for the mission and the planning and validation of all mobility and manipulation activities.

Comparing with the continuous tele-operation method, supervised tele-operation has its advantages. For instance, the rover must stop to wait for command sequences and it should be more intelligent. However, it has obvious advantages. The science activities are defined systematically and the operators need not be too nervous. Therefore, both tele-operation modes can be used respectively according to different terrains and missions. No matter which one is accepted, virtual simulation is indispensable.

III. State-Of-The-Art Of Rover Virtual Simulation

A. *General simulation tools used for rover research*

Various simulation tools are used by researchers to research on the rovers’ kinematics, dynamics, control and visualization. It is summarized in Table 1.

TABLE I. ROVER SIMULATION AND TOOL

	Researching contents	**Purposes**	**Simulation tools**
Forward Kinematics	Calculate the position and yaw angle of a rover according to feedback information of pitch and roll angles, motors’ and joints’ position	Determine the position and orientation of a rover (dead reckoning method)	Matlab, VC++, OpenGL, etc.
Inverse kinematics	Given the yaw angle, horizontal position of a rover and the path on known terrain, calculate the altitude, pitch and rock angles of the rover, as well as the position of motors and joints.	Analyze the stability and traversability of a rover while following a certain path	
Dynamics	Research on the wheel-soil interaction mechanics, multi-body dynamics, methods for solving differential equations with high efficiency, etc.	Analyze the dynamics performance such as vibratility and obstacle overcoming; it is also the basis of for designing control strategy	ADAMS, DADS, Vortex, etc.
Control strategy	Research on Control strategies of rover’s locomotion, path planning, path following and intelligent navigation	Develop program for rover control	Matlab, etc.
Visualization	Build visual virtual simulation environment according to topography and surface features of the planetary and rover’s configuration	Provide visualization platform for virtual simulation	Vega, 3D Max MultiGen Creator, etc.

1) Kinematics simulation: Professors M. Tarokh and G. J. McDermott of San Diego State University present a general approach to the kinematics modeling and analysis of articulated rovers traversing on rough terrain. Navigation, actuation and slip kinematics are identified and simulated with Matlab and Simulink toolbox (Fig. 1) [2]. Ju Hehua et al. provide real-time inverse kinematics with fuzzy logic and virtual sensors. VC++ software is used to construct 3D simulation platform [22]. Cai Zesu et al. analyze the forward and inverse kinematics of HIT-1 lunar rover prototype, and they use 3D modeling software MultiGen Creator to construct virtual lunar rover and environment for simulation [3].

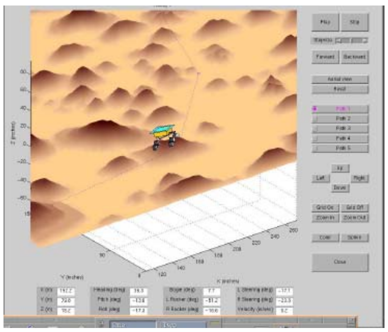

Figure 1. Kinematics simulation with Matlab

2) Dynamics simulation: R. A. Lindemann et al. of JPL simulate the motion of Mars rover with ADAMS and validate the effectiveness of virtual simulation by experiments [4]. P. Lamon and R. Siegwart of Autonomous System Laboratory (ASL), Swiss Federal Institute of Technology, use ODE software to do dynamics simulation for their Shrimp and SOLERO rovers (Fig. 2) [5]. Professor K. Yoshida of Space Robot Laboratory (SRL), Japanese Tohoku University, researches the rover's steering performance by terramechanics-based dynamics simulation with ODE [6]. Chinese researchers from Beijing University of Science and Technology, Huazhong University of Science and Technology and National Defense University of Science and Technology use ADAMS to simulate the dynamics performance and optimize mechanism [23][24]. Several kinds of lunar rover prototypes have been studied in RCAMC and ADAMS is used for dynamics simulation and analysis [25][26].

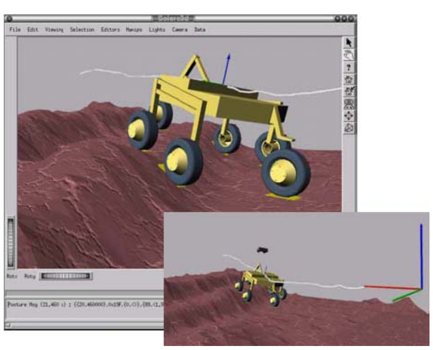

Figure 2. Dynamics simulation for SOLERO with ODE

3) Control simulation: C. M. Bellier of France simulate the path planning of Russian rover Marskhod with robot programming system ACT developed by C language [7]. K. Yoshida et al. simulate the path planning and following algorithm of a 4-wheel lunar rover with the terrain expressed by digital elevation map (DEM) [8]. Professor T. Howard et al. of Carnegie Mellon University (CMU) research the optimal trajectory generation method for wheeled mobile robots on rough terrain. The simulation work is shown in Fig. 3 [9]. The algorithm has been integrated to Coupled Layer Architecture for Robotic Autonomy (CLARAty) system of JPL. Liang Bin of Beijing Control Engineering Institute and Wang Wei of HIT present a self-adapting motor controlling method based on neural network (NN). Matlab is used to verify the robustness and effectiveness of the algorithm [27]. Joint simulation with Pro/E and DADS software is also done [28].

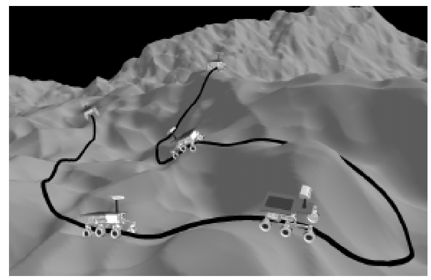

Figure 3. Optimal Trajectory Generation Simulation

B. Virtual simulation system developed for rovers

1) ROAMS, WITS and RSVP developed by JPL, USA

The Mars Technology Program, in conjunction with the Mars Science Laboratory Mission, is funding three complementary infrastructure elements: ROAMS, Web Interface for Tele-Science (WITS) and CLARAty [29].

ROAMS is a comprehensive physics-based simulator for planetary exploration rover vehicles. It includes rovers' mechanical subsystem, electrical subsystem, internal and external sensors, on-board resources, on-board control software, the terrain environment and the terrain/vehicle interactions. ROAMS can be used for stand-alone simulation, closed-loop simulation with on-board software and operator-in-the-loop simulation [10]. It includes rover kinematics, dynamics, navigation, locomotion and visualization. ROAMS provides simulation services for off-line analysis, as well as acting as a virtual rover platform for CLARAty control software (Fig. 4), which is reusable rover software architecture being developed in collaboration by JPL, NASA Ames, CMU and other institutions. A goal of the CLARAty development is to provide an open architecture for component algorithm developers to develop and integrate their capabilities into.

RSVP which has kinematics simulation ability is developed for rover tele-operation as mentioned above. WITS provides collaborative downlink data visualization and uplink activity planning for multiple Mars lander and rover missions. For the 2003 MER mission, WITS is the primary science operations tool for downlink data visualization and uplink science activity planning. It can build scripted sequences and execute them on a 3D simulated rover, which can be controlled interactively [30].

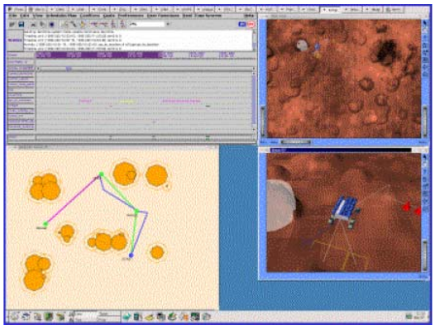

Figure 4. ROAMS and CLARAty closed loop simulation

2) RCET, RPET and RCAST of Europe

Mars Rover Chassis Evaluation Tools (RCET) are being developed to support the design of planetary rovers in Europe. The RCET, which is developed jointly by Contraves Space, EPFL, DLR and the others, can accurately predict rover performances of locomotion subsystem. It consists of a 2D rover simulator that uses a tractive prediction module for computing the wheel/ground interaction. 3D simulation can also be performed with the help of RoverGen.

The Rover Performance Evaluation Tool (RPET) consists of Rover Mobility Performance Evaluation Tool (RMPET) and Mobility Synthesis (MobSyn). The RMPET computes the mobility performance parameters such as drawbar pull, motion resistances, soil thrust, slippage and sinkage for a mobility system selected by the user for evaluation on a particular terrain[31].

RCAST was developed to characterize and optimize the ExoMars Rover mobility in support of the evaluation of locomotion subsystem designs before RCET is available (Fig.5). It uses AESCO Soft Soil Tire Model (AS2TM) software package for terramechanics [32].

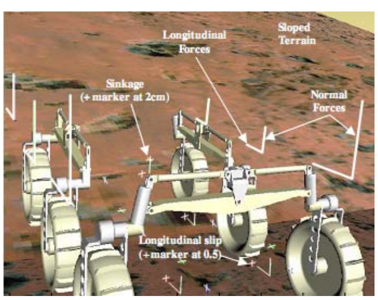

Figure 5. ExoMars simulation with RCAST

3) SpaceDyn developed by Tohoku University, Japan

RSL of Tohoku University developed dynamics simulation toolbox SpaceDyn with Matlab and it is successfully used for ETS-□ robot arm simulation and touchdown of the Hayabusa spacecraft on Itokawa. SpaceDyn is also used to simulate the motion dynamics of a rover with slip-based traction model [34] and steering characteristics of rover on loose soil based on terramechanics [35].

4) Simulation platform of Tsinghua University, China

Sun Zengqi and his colleagues of Tsinghua University researched on the test and simulation platform for lunar rover [36][37]. It provides modules for creating topography of the terrain and environmental components editor. With the terrain modules built in advance, virtual lunar environment is easy to construct. COM technology and used to support distributed simulation.

IV. DESIGH OF COMPREHENSIVE HIGH-FIDELITY/HIGH-SPEED SIMULATION SYSTME

A. Developing Trend of Lunar Rover Simuation System

1) High-speed dynamics simulation: High-speed dynamics simulation system is an important auxiliary tool for the tele-operation of lunar rover. While validating the command sequences, the simulation speed should not be too slow, because the entire exploration activity should be simulated. RSVP adopts kinematics simulation to get a higer speed. However, kinematics simulation can not show the phenomena such as slip-sinkage and side slip of the wheel very well while moving on deformable rough terrain of the moon. For instance, in 2005, the Spirit rover was stucked in the loose soil for several weeks. So that researchers are considering to develop the full dynamics simulation function of RSVP for the future Mars exploration missions [37]. The general dynamics simulaiton tools, either using contact model or tyre model, have low simulation speed because of large quantity of calculation. 3D Predictive display even requires real-time simulation, with high speed dynamics simulation as its basis.

2) High-fidelity lunar rover simulation: The surface of the moon is covered with a thick regolith layer composed of dust and rock clast. While moving on such deformable soil of the rough lunar terrain, severe slip-sinkage and side slip will occur to rover's wheels, making the vehicle decreasing tractive performace and deviating from scheduled path, even stucked in the soil. The trafficability, maneuverability and terrainability of a lunar rover can be evaluated effectively with the high-fidelity simulation system that could reflect the special phenomena of a lunar rover. So that it can be used during the R&D phase of a rover to optimize the mechanism, verify the control strategy, test the performance, etc. High-fidelity and high-speed simulation is contradictory due to the limitation of computer's calculation speed. But high-fidelity simulation is the basis of high-speed simulation. Simplify the high-fidelity models and calculating process to improve simulation speed and get a compromised fidelity is feasible.

3) Comprehensive simulation system for lunar rover: ROAMS of a America is a good example for Mars rover. The lunar rover simulation system should also have the ability of modeling, kinematics, dynamics, control and visualization. And it is necessary to provide simulation of various resolution and switch between high-fidelity and high-speed simulation.

B. Architecture Design of Comprehensive High-fidelity/ High-speed Simulation System forLunar Rover

Fig. 6 is the architecture diagram of lunar rover's comprehensive virtual simulation system. It is composed of

Lunar Rover Modeling, Analysis and Simulation (LRMAS) and Interactive Virtual Lunar Rover Environment (IVLRE). LRMAS is a comprehensive simulation system similar to ROAMS. Control commands of three levels from itself, IVLRE or other control software are accepted, i.e. the goals, paths and motor's position. User's can control the virtual lunar rover interactively with IVLRE. IVLRE constructs virtual lunar environment with terrain components or images from the real rover. Then DEM terrain data are generated for LRMAS. It can also calculate the mechanics parameters of lunar soil for LRMAS. It can be further developed for lunar rover tele-operation based on 3D predictive display. Different resolution of simulation system can be selected to meet different actual demands, including high-fidelity dynamics simulation, high-speed dynamics simulation and kinematics simulation.

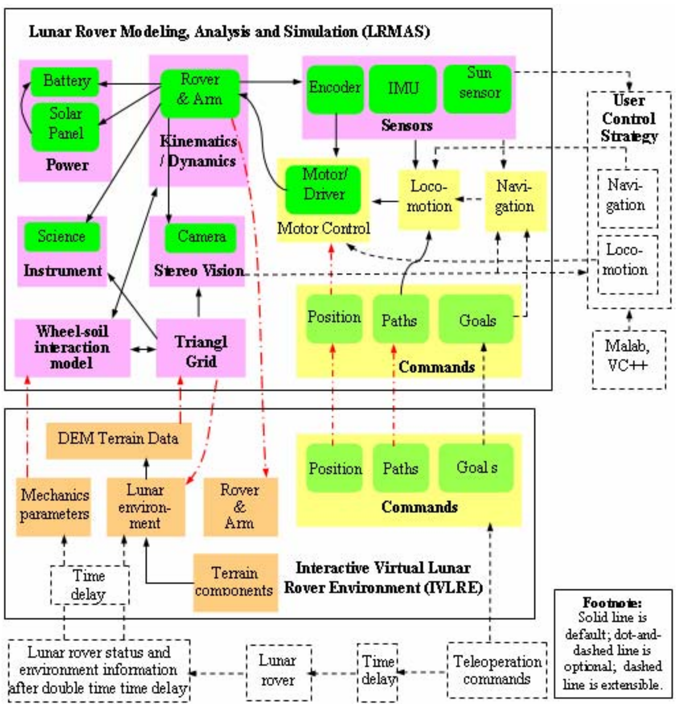

Figure 6. Diagram for lunar rover's comprehensive simulation system

C. *Key Technologies for the simulation system*

1) *Lunar rover's terramechanics:* It deals with the wheel-soil interaction mechanics and it is the bottle-neck for high-fidelity simulation. Conventional terramechanics for cars should be extended to the lunar rover with experiments.

2) *Recursive multi-body dynamics for lunar rover.* This is a key issue for improving simulation speed. The tree structure of lunar rover makes it possible to realize dynamics simulation with thorough recursive method based on relative coordinates.

3) *Virtual reality.* Updating the visual lunar environment and rover state and displaying them with high speed are very important.

4) *Technologies for real-time simulation. They are* necessary for the realization of hardware-in-loop simulation and operator-in-loop simulation.

D. *Benefit and implementation mechanism of the system*

As a comprehensive simulation system, it combines the performance of software such as ROAMS and WITS. Not only can it be used as platform for design, evaluation, test and control of a lunar rover during the R&D phase, but also it can support 3D predictive display for successive tele-operation, validate commands sequence for supervision tele-operation of a rover.

The kinematics and dynamics module is composed of multi-body kinematics and dynamics model of the rover. It interacts with the wheel-soil interaction model to compute the state of the rover. The rover's state is used by the virtual sensors such as the encoders, IMU and sun sensor as well as the power model, to simulate the sensor and power state of the rover. The information can also be used by the control modules including locomotion and navigation module. The rover state is also used to send messages to the IVLRE to update the 3D graphics visualization. The terramechanics parameters can be set up by users or identified from the real rover for wheel-terrain interaction model. The terrain data is transformed to triangle grid according to virtual terrain or photos sent back by the rover.

V. RENCENT AND FUTURE WORK IN RCAMC OF HIT

RCMAC has been researching on the comprehensive high-fidelity/high-speed simulation system according to the designed architecture. Some useful results of lunar rover terramechanics and recursive dynamics for simulation system has been obtained. Fig. 7 shows the simulation result of lunar rover's single wheel with newly developed lunar rover terramchanics. Comparing with the results measured by a single wheel testbed, the results of sinkage, resistance torque, slip ratio, sustaining force and drawbar pull verify the simulation results.

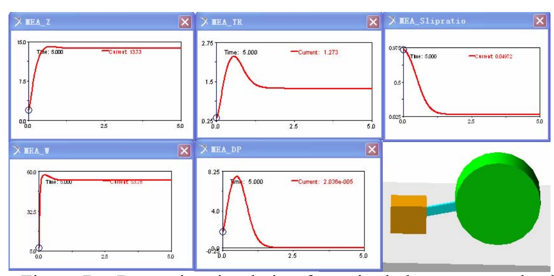

Figure 7. Dynamics simulation for a single lunar rover wheel

In the future, the lunar rover's terramechanics and recursive dynamics will be researched more systematically and technologies for virtual reality and real-time simulation of lunar rover will also be researched on. It is hoped that the entire comprehensive high-fidelity/high-speed simulation system can be developed successfully and partly be used in Lunar exploration activities.

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