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A PRIORITY METHOD OF CRUISE DIRECTION FOR THE LUNAR ROVER

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During the exploration of the YuTu lunar rover on Moon, as one of the key missions of the teleoperation system, the selection of the rover's cruise direction should be considered firstly. It is restricted by the rover's operating constraints, the relative position of the Sun-Earth-Moon, the trafficability, etc. The essential factors of the rover's operating constraints are listed, including the power balance, the obscuration of the communication, the limited moving range of the manipulator, the shadow of the solar array, the sunlight condition and the requirements of the scientific exploration. The final selection provides the direction for the local path planning and the exploration of the lunar rover. The mission of the YuTu lunar rover on Moon is divided into three phases, which including interactive imaging, test and operating. At first, this paper gives the requirement analysis of the rover cruise direction on Moon. Then the method of the synthesized analysis, which is a priority method of cruise direction, is introduced. The model of the analysis method is built and the judgment condition is determined. Finally, the feasibility of this method is approved by simulation and validated by the rover's exploration on Moon.

I. BACKGROUND

Lunar Rover operation is a complex and incessant progress which contains multi-interactions between the rover and ground teleoperation center. This challengeable remote control operating model is obviously different from China's previous spacecrafts. The control model of the lunar rover has following features: long distance, complex tasks of multi-model and multi-constrains, un-repeatable, non-structural and un-predictable lunar environment, high frequency and long duration mission supporting operations, requirements of synchronous simulation etc. Therefore, a ground teleoperation system[1] is developed to meet the requirements. This control system has solved the difficult problems which can be expected in the future rover missions.

During the exploration of the YuTu lunar rover on Moon, as one of the key missions of the teleoperation system, the selection of the rover's cruise direction should be considered firstly. It is restricted by the rover's operating constraints, the relative position of the Sun-Earth-Moon, the trafficability, etc. The essential factors of the rover's operating constraints are listed, including the power balance, the obscuration of the communication, the limited moving range of the manipulator, the shadow of the solar array, the sunlight condition and the requirements of the scientific exploration. The final selection provides the direction for the local path planning and the exploration of the lunar rover.

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II. RESEARCH STATEMENT IN WORLD

Up to date, 10 rovers have been successfully launched and landed on Moon and Mars since 1960s. 6 lunar rovers and 4 mars rovers were developed by nations: one by China, two by Russia, and 7 rovers by USA. Several rovers are introduced as follows aiming at the cruise route.

II.I Lunokhod lunar rover

Lunokhod-1 was launched in November 1970.It was the first rover landed on Moon. Lunokhod-2, launched in January 1973, was similar to Lunokhod-1. Both rovers were teleoperated. The operating process is as follows. First the rover transmitted the television pictures from Moon. The operators on the earth received the signal and analyzed to plan a short path and the action sequence. Then the instructions were sent to the rover and executed by the rover. When the rover finished the planned path, it stopped and waited for the next planned mission. The mission planning was made by a team which contains a calculation commander, a navigator, a driver, an antennae operator and an engineer of the rover[2].

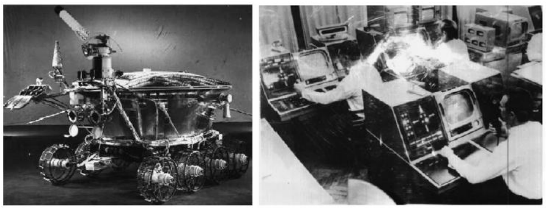


Fig. 1: Lunokhod 1 and its control station (NPO Lavochkina museum)

The total mileage of Lunokhod 1 was approximately 10km， and the total mileage of Lunokhod 2 was approximately 37km. Fig. 2 shows the cruise route of Lunokhod-2[3].

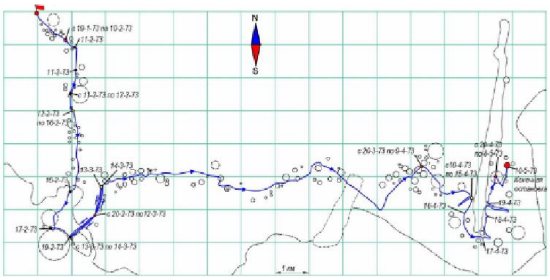


Fig. 2: The cruise route of Lunokhod 2 on Moon

II.II Sojourner rover

Sojourner was launched in December 1996. It was the rover of the Mars Pathfinder explorer, which was launched by the USA. It is the first rover to cruise on another planet. The operators made the action planning with the planner Rover Control Workstation(RCW), which provided the visualization for vehicle traverse planning, a command interface, constraint checking for individual commands and some resource estimation. The RCW made decisions include where, what, and when the rover can reach the target, but it was never intended for automated goal-based planning[2]. The supervisory control interfaces for Sojourner on Mars in NASA JPL is shown as Fig. 3.

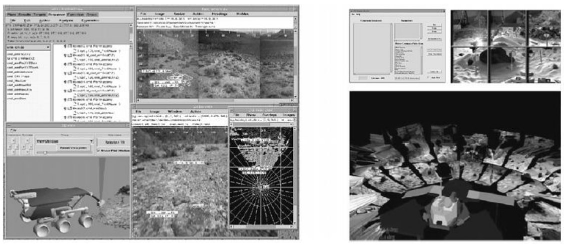


Fig. 3: Supervisory control interfaces for Sojourner on Mars in NASA JPL (left: Numerous command and analysis tools; right: The rover control workstation)

Sojourner covered more than 100 meters around the lander, operated over 83 sols (Martian days). Fig. 3 shows the mission path of Sojourner[4]. The mission planning of the Sojourner relied on the scientists and the engineers on the earth and needed the help of the lander. Operators selected waypoints along these safe paths, at intervals of 1-2 meters, as intermediate goals for autonomous navigation.

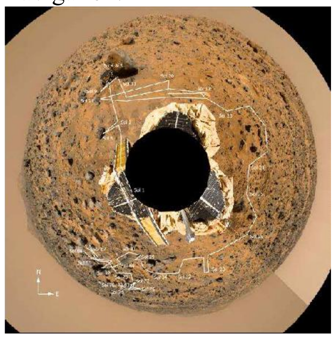


Fig. 4: The cruise route of Sojourner on Mars

II.III Mars Exploration Rovers

Spirit (MER-A) was launched in June 2003, along with Opportunity (MER-B), which was launched in July 2003, are the missions of Mars exploration in 2003 by the NASA. The team of MER developed the Science Activity Planner (SAP) for the science operations. SAP utilizes a variety of visualization and planning capabilities to enable the mission operations team to direct the activities of the Spirit and Opportunity rovers, shown in Fig. 5[5]. The Cylindrical (top), polar-azimuthal (bottom-left), and 3D (bottom right) renderings of a mosaic of images acquired by Opportunity are shown in Fig. 5.

Fig. 5: The Science Activity Planner

The mission of Spirit was completed after the last contact with Spirit made by NASA on March 22th, 2011. Opportunity is still operating on Mars now. Comparing to Sojourner, Mars Exploration Rovers (Spirit and Opportunity) performed better in autonomous operations and they can traverse far from their lander. It takes 26 minutes for the signal to go and return because of the distance between Mars and Earth, which made the real-time control infeasible. Therefore the rovers used autonomous navigation technology is adopted, which contains a global planner basing on the Field D* algorithm and a local planner called Grid-based Estimation of Surface Traversability Applied to Local Terrain (GESTALT). Besides line-of-sight and the resource constrains made the situation more complicated. Thereby, a command sequence lays out all activities to be performed by the rover during the sol is given at the beginning of the sol. The rover then executes the command sequence without any human intervention. In general, before the rover shuts down for the night, it will send data back to Earth. The data is then used to plan activities for the following sol. Fig. 6 shows the traverse route of the Spirit and Opportunity [6].

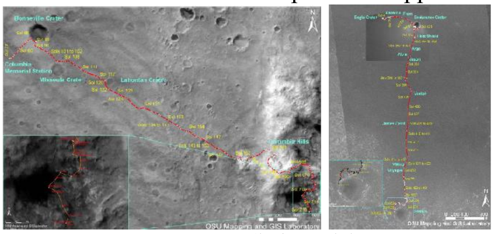


Fig. 6: MER Traverse Map (left: Spirit traverse map up to Sol 718; right: Opportunity traverse map up to Sol 698)

II.VI MSL Mars Rovers

Curiosity (MSL), also called Mars Science Laboratory was launched in November 2011. It is the fourth rover on Mars. The operators developed a method called mission-directed path planning for the MSL Mars exploration. The mission is planned on base of the time, recourse, operation constraints and other important factors. And a path planner called Temporal Mission Planner for the Exploration of Shadowed Terrain (TEMPEST) is given to implement the path planning[7]. There are six models in TEMPEST. Fig. 7 shows the common interrelationships in TEMPEST and the Mission Support Center.

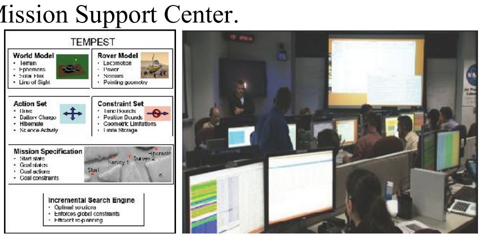


Fig. 7: Mission Planning Key Components and Mission Support Center

The main algorithm in TEMPEST is Incremental Search Engine (ISE). ISE is an abstract of the D* algorithm, which preserves the high efficiency of planning and re-planning, and can adapt more than two global constraints. TEMPEST has been successfully used in the project called The Life in the Atacama (LITA) and played an important role in the desert detection and the desert life looking[7]. Fig. 8 shows the moving route of MSL[8].

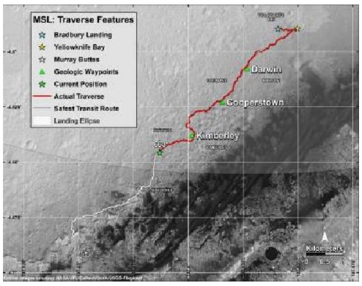


Fig. 8: Curiosity Rover's Traverse (First 663 Sols on Mars)

II.V YuTu lunar rover

YuTu rover was launched in December 2013. It is the first China rover landed on Moon. The operators developed the teleoperation system to control the YuTu lunar rover[1]. With some autonomous functions on the rover, the teleoperation system successfully supported the exploration of the YuTu rover. The mission control interfaces are shown as Fig. 9.

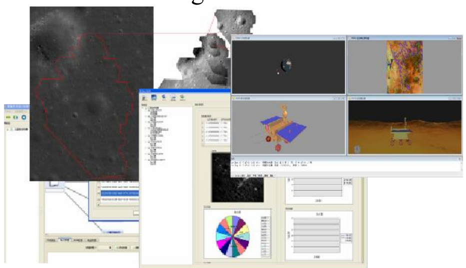


Fig. 9: Mission Control Interfaces

The total mileage of the YuTu rover is approximately 118.9m. The mission of the YuTu rover on Moon is divided into three phases, which including interactive imaging, test and operating. Fig. 10 shows the moving route of the YuTu rover.

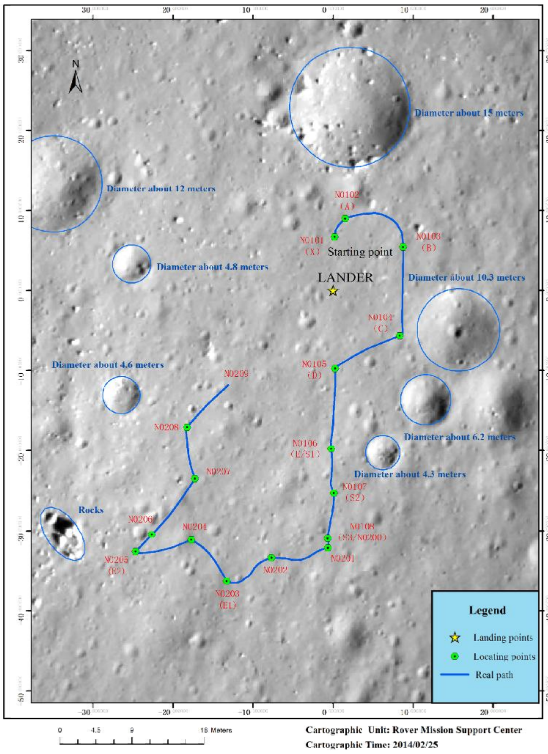


Fig. 10: YuTu Rover's Traverse

III. REQUIREMENT ANALYSIS OF CRUISE DIRECTION SELECTION

The mission of the YuTu rover on Moon is divided into three phases, which including interactive imaging, test and operating. In the first phase, which is interactive imaging, the YuTu rover should traverse five point A、 B、C、D、E, shown in Fig. 11. In the phase of test and operating, the YuTu rover should complete moving exploration and in-situ exploration. The cruise direction optimization is one of the key factors considered chiefly in these three phases.

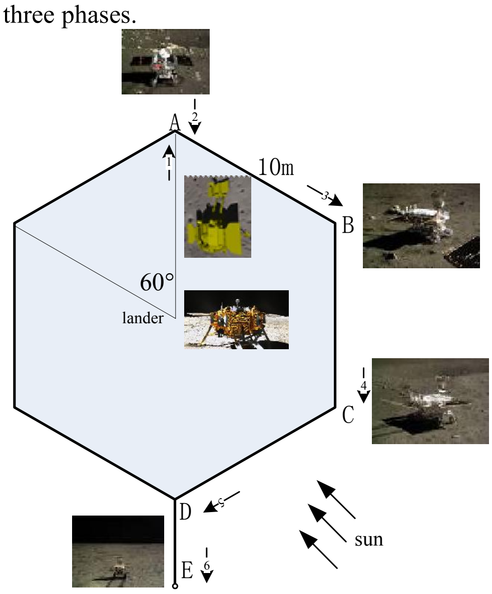


Fig. 11 Sketch Map of YuTu Rover's Traverse in the Phase of Interactive Imaging

In general, based on the design requirement, the YuTu Rover is operating at the sun elevation angle which is more than 5°. And it will be into dormancy state at the sun elevation angle which is less than 5°. In the operating period, the cruise direction optimization of the YuTu Rover is restricted by many constrains, which including Communication Conditions, Power Require, Terrain Texture Map, Ephemeris, Thermal conditions, Geometric Interferences, and so on.

In all case, the Communication Conditions and Power Require must be met with. In a word, in the three phases, which including interactive imaging, test and operating, the cruise direction optimization of the YuTu Rover should be under all constrains as good as possible.

IV. METHOD OF CRUISE DIRECTION SELECTION

During the lunar exploration, the cruise direction optimization of the Lunar Rover is determined by mission planning. Inputs of Mission Planning include Initial Position/Attitude, Planning Start Time, Target Position, Lunar DEM, Terrain Texture Map, Ephemeris, Current Capacity of Storage Battery, Power Require, Communication Conditions, Rover Model, Rover Resource and Action Constraints, which is shown in Fig.12.

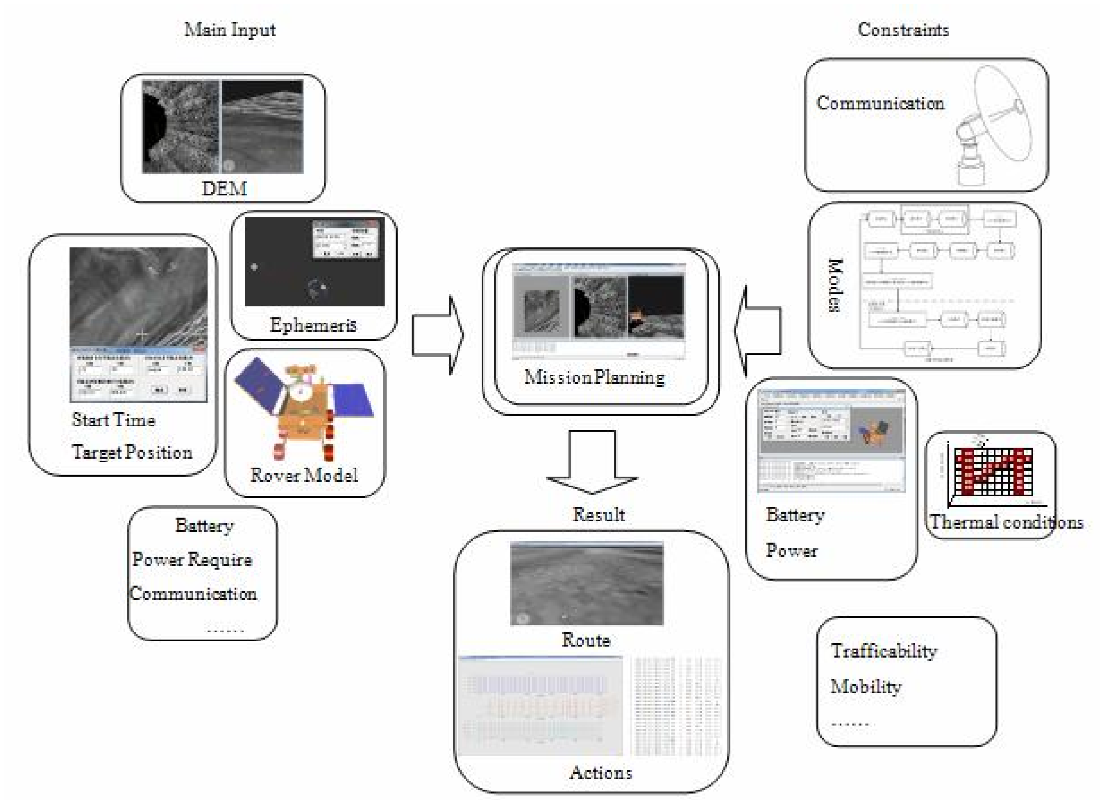


Fig. 12 Input and Restriction of YuTu Rover's Cruise Direction Optimization

The constraints conditions of YuTu rover mission planning, which are the conditions of cruise direction optimization, are shown as follows.

Constraints of TT&C/data transmission include deployment spot of ground station and Data Receiving Station, the lowest elevation angle of the antenna, geometric interferences between TT&C antenna/data transmission antenna and +Y solar array/mast, and rover attitude, etc. TT&C plays the primary role in the condition of lunar rover's normal operation. It is also crucial to ensure the omni-antenna is normally operated during data transmission.

Constraints of operation modes include Types of operation modes and modes entering conditions, etc.

Constraints of energy supply and power allocation include time consumption/power consumption, solar array capability and control, charging and discharging characteristics, etc. Power balance plays the important role in the condition of lunar rover's normal operation.

Constrains of detection coverage traversability and rover mobility include geomorphology and mechanical behaviors of detection voverage, rover mobility, TT&C/data transmission –ready attitude, etc.

Constraints of mechanism performance include +Y solar array motion constraint, mast motion constraint, omni-antenna constraint, etc.

Constraints of thermal control include thermal conditions under rover operation, etc.

During the cruise direction optimization process of the rover, the basic principles of mission planning are: In basis of DEM of detection area captured by Satellite, DEM obtained by stereo visual system, longitude/latitude of moon centered inertial coordinate system, rover position in DEM, target position in DEM, current time, current operation mode and status, with satisfaction of multiple constraints including TT&C, thermal control, energy, mobility operation modes transition, based on mosaic graph planning method, adopt predicate logics and constraint planning theory, using time cost of behaviour as heuristic optimization and SD*Lite planning method to determine the route planning of current/target positions and behavior sequence of the rover. The function matrix of the cruise direction optimization is shown in Fig.13.

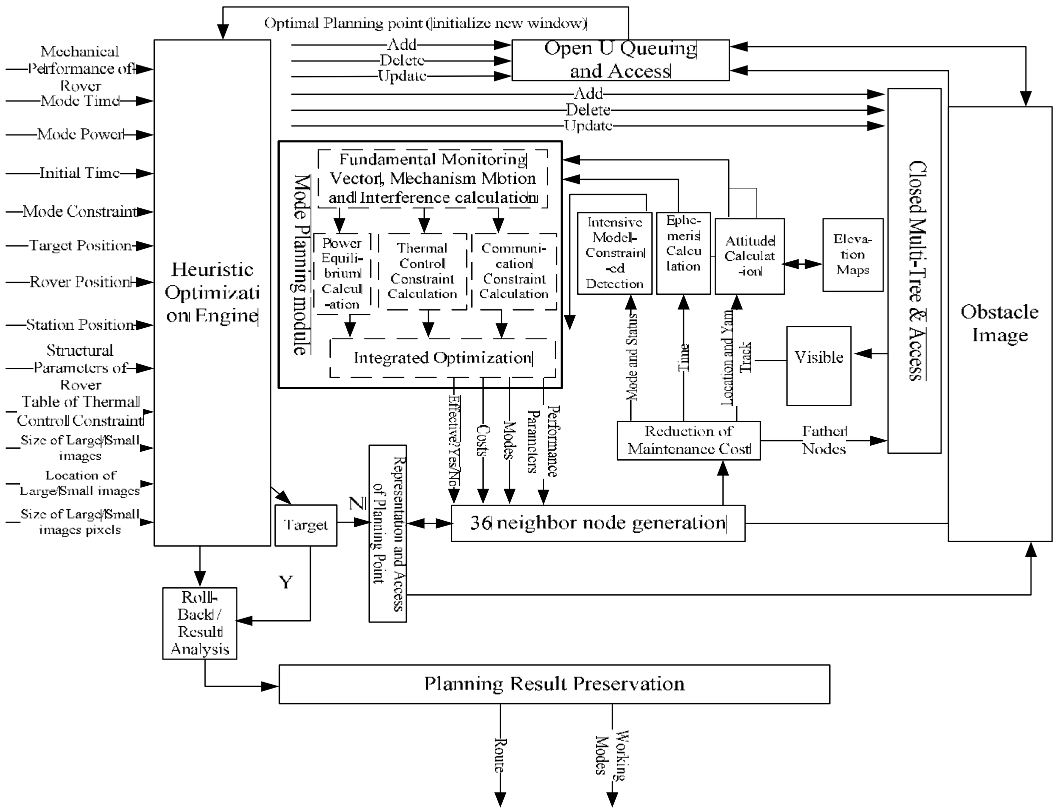


Fig. 13 Function Matrix of YuTu Rover's Cruise Direction Optimization

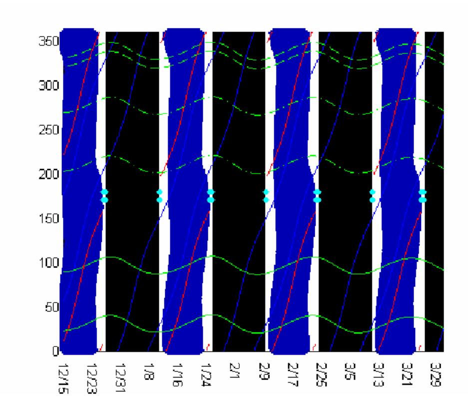
V. SIMULATION AND IN-ORBIT VERIFICATION

V.I Simulation

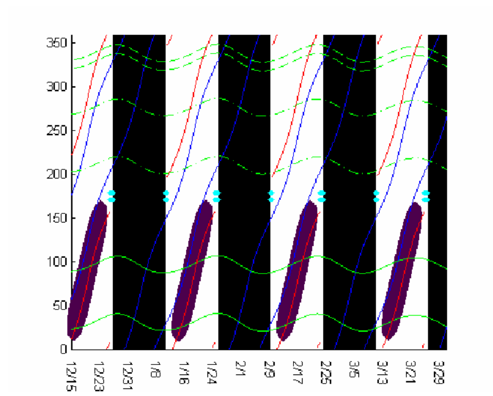
On the assumption that three-axis attitudes of the rover are 0, the lander/rover separation start time is set to Dec.15th 2013, the landing site is (44.1°N，20.3°W).

The cruise direction optimization angle is defined as: north – 0, north east – positive, north west – negative. The cruise direction optimization analysis of the rover during the first three lunar days is shown in Fig.14. Black area indicates lunar night, white and coloured area indicates available area for cruising of the rover, between lines area of blue stripes indicates solar sensor constraints area, between lines area of green stripes indicates mast to ground constraints area, cyan area indicates lunar night-dormancy constraints area, and between lines area of red stripes indicates obscuration constraints area.

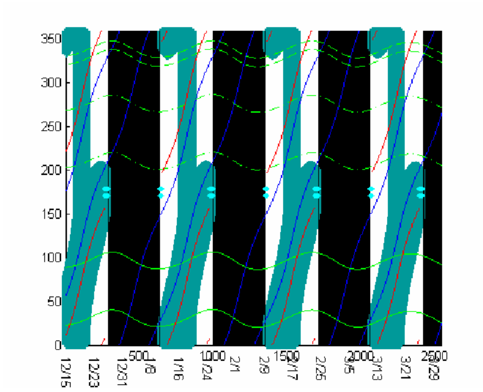
As shown in Fig.14, majority of the rover movement cruise direction optimization are satisfactory with requirements of power balance. Basically all area are satisfactory with requirements of solar incidence angle, which is more than 45°, and only a fraction of area are less than 20°.



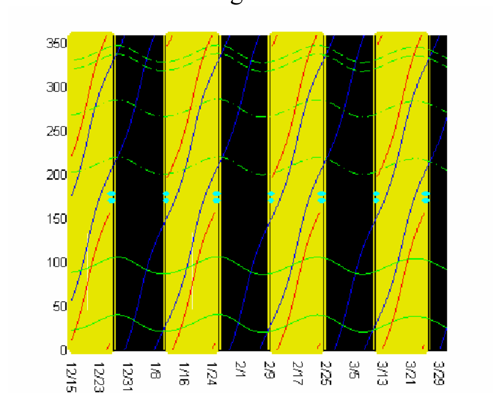
a) cruise direction optimization based on power balance



b) cruise direction optimization based on solar incidence angle less than 20°



c) cruise direction optimization based on solar incidence angle between 20° and 45°



d) cruise direction optimization based on solar incidence angle more than 45°

Fig. 14 Sketch Map of Simulation of Cruise Direction

V.II In-orbit validation

Taking the cruise direction optimization planning results of interactive imaging for example, yellow real line on the left image indicates the optimized cruise direction route that shown in Fig.15. It proved that the method of cruise direction optimization presented in this paper is feasible after the comparison with results shown in Fig.11.

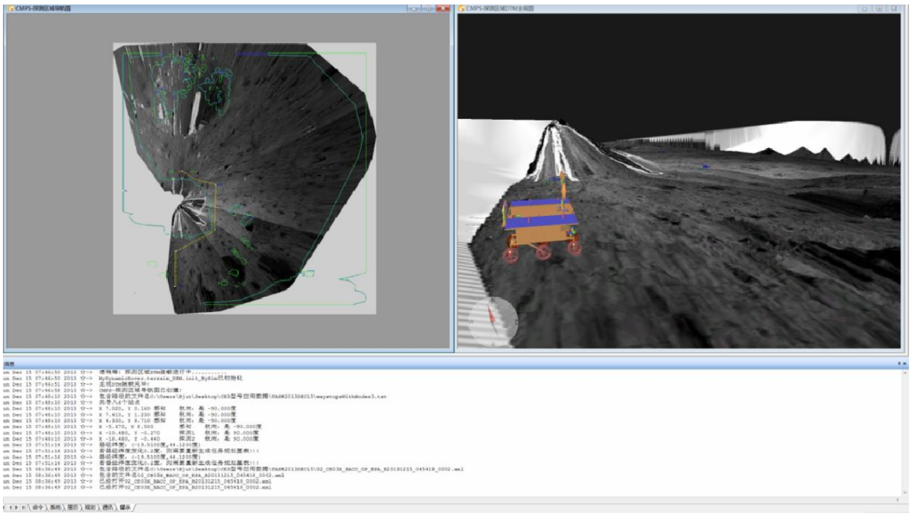


Fig. 15 Sketch Map of Cruise Direction Planning in the Phase of Interactive Imaging

VI. CONCLUSIONS

This paper studies on the cruise direction of the Lunar Rover base on the teleoperation system, the major work is stated as follows:

1) Based on the research statement in world, the requirement analysis, which is in the phases of interactive imaging, test and operating, is accomplished.

2) The cruise direction optimization of the Lunar Rover, which is a priority method of cruise direction, is determined by mission planning. Predicate logics, constraint planning theory and time cost of behaviour are used as heuristic optimization to achieve the route planning of current/target positions and behaviour sequence of the rover.

3) The feasibility of this method is approved by simulation test and validated by the rover exploration on Moon. It is clear that the method of cruise direction optimization presented in this paper is correct and achievable.

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