The Operations of China's First Lunar Rover

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Chang'E-3, the second phase of the China Lunar Exploration Project, consisting of a Lander and a rover, is planned to be launched in 2013. The rover is a highly autonomous six-wheeled terrain vehicle on the surface of the moon. The rover has 3 pair of "eyes": navigation cameras and panoramic cameras, both mounted on a mast, hazard avoidance cameras mounted on the lower portion on the front of the rover. The cameras work in cooperation by providing a complementary view of the terrain and aid in rover navigation and also perform science investigations. Additionally, the rover has a robotic arm which has flexibility through three joints: shoulder, elbow and wrist. The robotic arm enables the scientific instrument at the end of the arm to extend, bend, and angle precisely against a rock or soil to analyze the elemental composition of them. Beijing Aerospace Control Centre (BACC), as the control centre of the China Lunar Exploration Project, faces big challenges to operate the China's first lunar rover.

This paper gives an overview over the rover setup, describes how the operations of rover in practice is designed and how the control system of the rover in BACC is built. It also details the necessary adaptation of the current BACC infrastructure as well as how to meet the demanding requirements of the rover operations within a relatively short time in a costly manner. Finally it is described which specific tools are utilized and how the interfaces of each subsystem are handled.

Introduction

China Lunar Exploration Program (CLEP) comprises three stages. The objections of three stages are orbit, land and return respectively. Named after the Chinese goddess of the Moon, Chang'e-1 was launched in October 2007 and ended its life by crashing the moon. Chang'e-2 was launched in October 2010 and is circling Lagrange 2 in the extension lifetime. Chang'e-3, involving a Lander and a rover, is scheduled to land probes on the moon in 2013 and carry out point detection and rove detection on the moon surface. The lunar rover is the one which will traverse on the moon, and it's also the first China's mobile robot working on a celestial body besides earth.

The rover is six-wheeled, solar-powered robot which can handle the moon's gravity, and withstand intense cosmic rays and temperature differences that run between minus-180 degrees Celsius at night and 150 degrees in the day. The rover has 3 pairs of "eyes": navigation and panoramic cameras, both mounted on a mast, and hazard avoidance cameras mounted on the lower portion on the front of the rover. The cameras work in cooperation by providing a complementary view of the terrain and aid in rover navigation and also perform science investigations. Additionally, the rover has a robotic arm which has flexibility through three joints: shoulder, elbow and wrist. The robotic arm enables the scientific instrument (APXS, Alpha Particle X-Ray Spectrometer) at the end of the arm to extend, bend, and angle precisely against a rock or soil to analyze the elemental compositions of them. An illustration model of the rover is shown in Figure 1below.

The rover six wheels mount on a rocker –bogie suspension system that ensures wheels remain on the ground while driving over rough terrain. The design allows the rover to go over obstacles or through holes. Each wheel has cleats, providing grip for climbing in soft sand and scrambling over rocks. Each wheel also has its own motor. The two front and two rear wheels each have individual steering motors. This allows the vehicle to turn in place, a full revolution, and to swerve and curve, making arching turns. The rover is designed to withstand a tilt of certain

degrees in some direction without overturning. The rover has auto control capability. The onboard software causes it to stop several steps to observe, understand the terrain into which it has driven, and plan path.
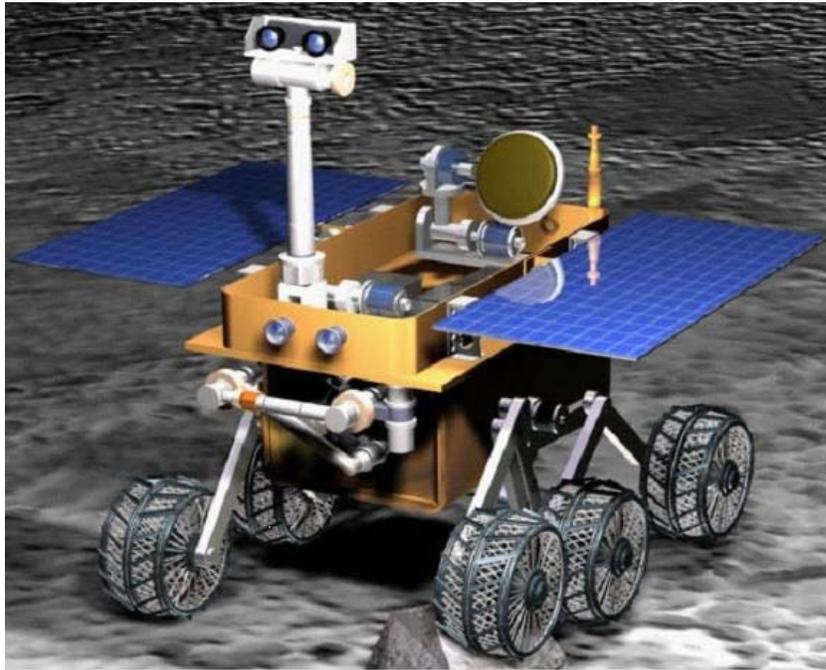

Figure 1   the rover model

Operations Concept

Following a launch, a cruise phase lasting around 5 days would culminate in Moon orbit insertion .The probe around the moon would run nearly 10 days and end with the entry, descent and landing (EDL) phase. The moving of the rover off the lander is called the egress phase of the mission. After that, the Lander and the rover will work separately on the moon. The orbit of Chang'e-3 is similar with Chang'e-2 before EDL and the electrical equipments of the rover turn on after landing. The overall mission profile is as the followings in Figure 2:
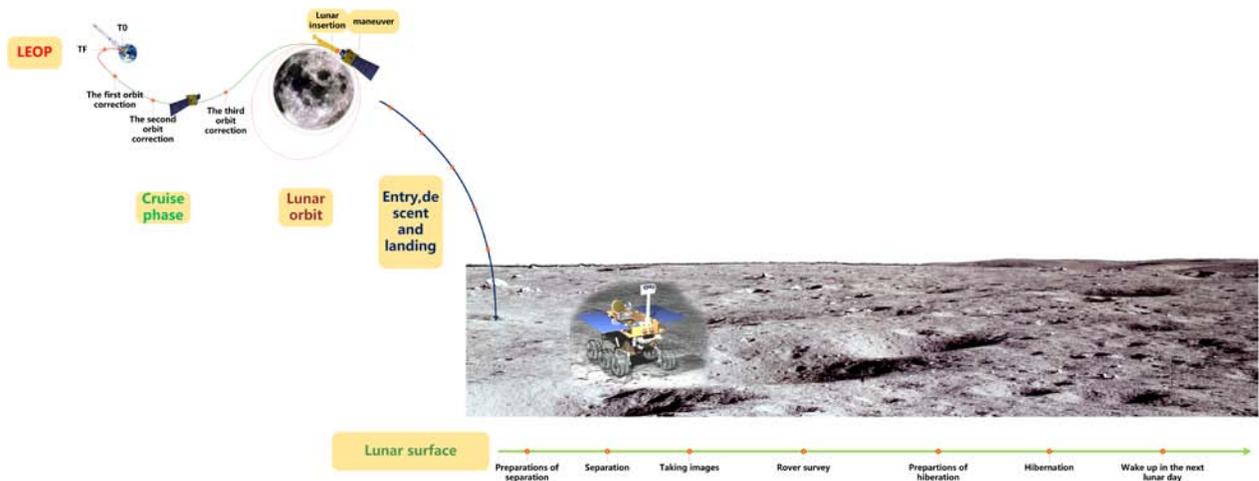

Figure 2   the overall mission profile of Chang'e-3

The rover has a low-gain and a high-gain antenna. The low-gain antenna is Omni directional, and transmits data at a low rate to Deep Space Network antennas on Earth. The high-gain antenna is directional and steerable, and can transmit data to Earth at a higher rate. The rover also uses the UHF antennas to communicate with the Lander. The Lander relays data from the rover to Earth.

The rover works only in the lunar day (around 13 earth days) and hibernates in the lunar night (around 14 earth days). The domestic Deep Space Network system can provide 11~17 hours each Earth day for communications, to upload commands for execution and for download of all science and housekeeping data. But sharing of the Deep Space Network with the Lander gave restricted ground contact times which should been taken into account an operational solution by BACC.

The rover has several work modes which are moving, recharging, photographing, science experiment, download science data and hibernate. Normally, the rover won't take two modes in parallel except recharging. This means the rover uses the "wait and move" mode. In this context, direct teleoperation of the rover is possible and adopts for most cases as the round trip communication time between Earth and Moon ranges only several seconds.

The ground segments of the rover include various roles, as described in Figure 3 below.

- Deep space network: the two domestic deep space antennas have the full capability of uplink and downlink, but can't provide the full coverage of the rover. The ESA Deep Space Station Malague in South America is anticipates supporting the rover as well as the Lander to enlarge the coverage. Keeping the low-gain antenna of the rover to point to the earth is necessary when walking.
- High bit rate data receiving station: science data including the stereo images downloads via the high-gain antenna, the two stations (KM and MY) and the Deep space network receive them when the high –gain antenna pointing to the earth.
- Flight control team: in charge of data processing, mission planning, flight dynamics, uplink of the commands to the probe, control of the flow of science/housekeeping data back to Earth from the probe as well as the teleoperation of the rover.
- Science operation team: provide the science equipments operations request and the science target, for example, where the rover should to go and stop? Which rock the robotic arm would like to explore?
- Project team: maintains a rover and the indoor test facility for testing and modelling of situations on Moon. The test rover is fully instrumented and nearly identical to the one on the moon. The rover is used for a simulation of the incident in some cases (such as rapped in soft soil) and validates the control strategy before sending command sequence to the rover.
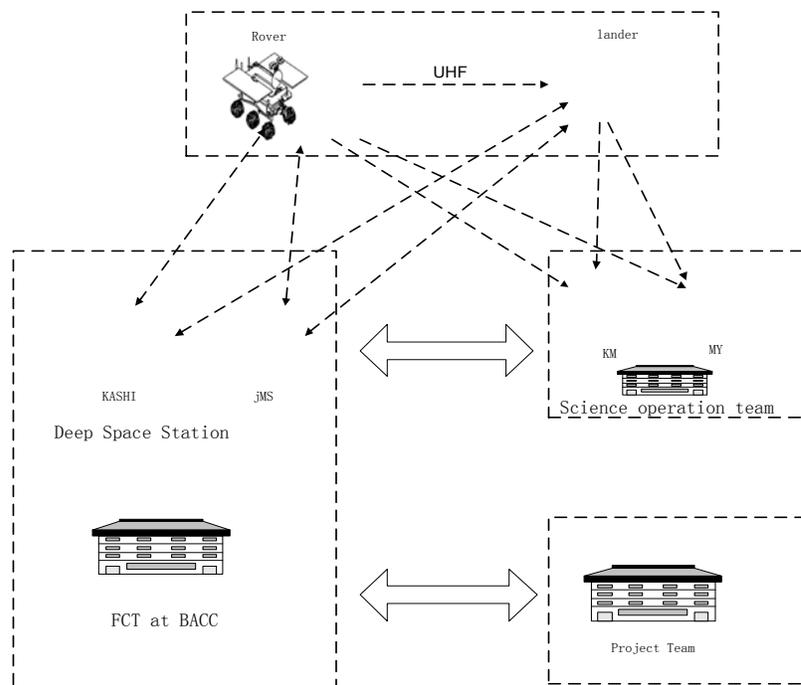
Fig 3 "The Big Picture"--- BACC view of the Ops Concept

How to Do It

Beijing Aerospace Control Centre (BACC), as the control centre of China Lunar Exploration Project, faces big challenges to operate the China's first lunar rover.

The current BACC infrastructure family includes some kernels and also a number of related tools which plug-in to it to satisfy different mission characteristics. The kernels and tools are composed of:
- Mission control system: receiving, processing and visualization of telemetry, sending telecommands and verifying their execution.
- flight dynamics system: orbit determination and prediction, attitude determination and monitoring, manoeuvre control and optimisation
- Data distribution system
- Database system
- Simulation system
- Mission planning tool
- Failure diagnosis tool

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From the very beginning, the design drivers of the Chang'e-3 ground segment in BACC are compliant with the following rules as two probes need to be operated:
- Re-use of existing infrastructure optimizing reliability, cost effectiveness: following mission commonality analysis as the orbit of Chang'e-3 is similar with Chan'g-2 and the rover's equipments turn off before landing, it means the Lander ground segment can be set up by strongly re-using the applicable software developed by precursor missions---Chang'e-2. In this way, the Lander ground system is founded with a relatively short time in a costly manner.
- Development of specific mission requirements: mission specific functionality, the teleoperatoin system of the rover, as delta to the existing baselines, are consistent with the rover objectives and are valid, feasible and safe over the life time of the mission.

The Teleoperation System Overall Architecture

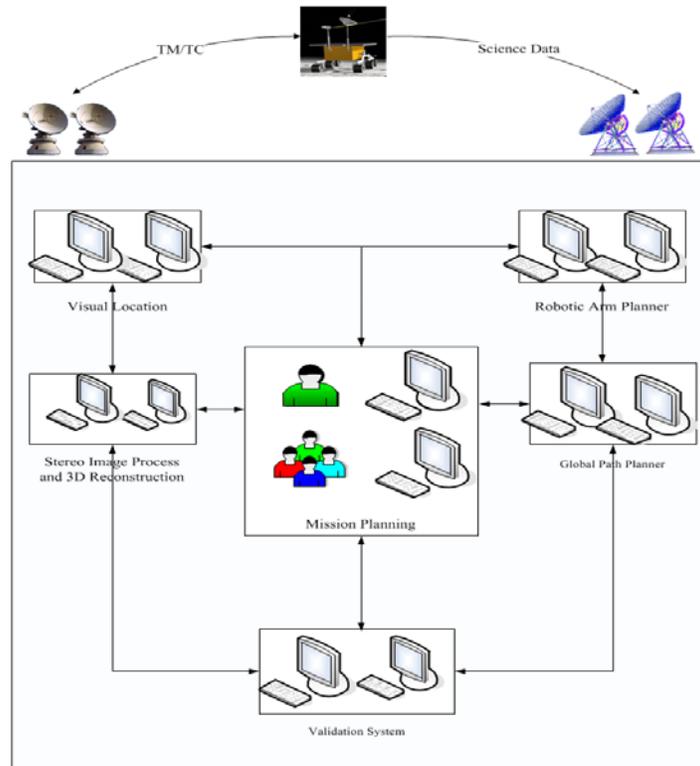The concept developed into the architecture in figure 4.

Fig 4   the overall architecture of the teleoperation system

Stereo Image Process and 3D Reconstruction is responsible for topographic mapping that is image acquisition, camera calibration, features extraction, stereo matching and 3D reconstruction .The outputs are the DEM (Digital Elevation Model) and DOM (Digital Orthogonal Map). Stereo Images from the navigation, panoramic and hazard avoidance cameras are the basis of the teleoperation system. According to the visual perception theory, we can compute the 3D position of the points in the giving pair of images, and further more, a complete surface reconstruction map of the terrain around the rover. These maps will be used for pointing science instruments at very specific points of interest, or targets. The problem of the system is the balance between the time constraints and the accuracy of processing the great mounts of the stereo images.

Visual Localization (the position and orientation) of the vehicle is a technique that is more effective at producing more accurate position and attitude than IMU (Inertia Measurement Unit), onboard sensors, traditional radio ranging and VLBI (Very Long Baseline Interferometry). Localization of the Lander and rover is of fundamental importance to understanding where the vehicles have traversed and how to get the rover to new location. Stereo image pairs from the vehicle and high-resolution orbital images from Chang'e-2 were taken to determine the Lander and the rover's position. Visual odometry and bundle-adjustment technologies were applied to overcome wheel slippages, azimuthal angle drift and other navigation errors. As images from lunar surface normally without obvious features, it is particularly challenging to matching and producing the solutions in no more than several minutes.

Mission Planning involves generating the mission-level path, path-dependent activity sequence and a low-level command sequence. To the rover's mission planning, the big problem is to plan the feasible path and the

activity in the path simultaneously. The path and the activity are not only influenced by each other, but also change with time, terrain, visibility, power and thermal. The Mission Planning has the following functionalities:

- State modelling
- Resource modelling
- Command /activity/sequence database
- Rule---- deriving activity, auto-scheduling, conflict checking
- Plan optimization
- Re-plan, flexible plan
- Plan visualisation
- Input and output data

Global Path Planner computes the global optimal path between given start and end points, considering vehicle dynamics, and terrain topography. The cost function and objective function can be selected via different optimization goals. For the lunar rover, there are three levels path planning:

- Mission-level path: select a traversable path in Mission Planning. This is a large scale and long distance path planning, normally several hundreds of meters. It pays more attentions on the elements changing with time and outputs the navigation point and the activities on it.
- Global-level path: find a traversable path in two navigation points from the Mission Planning. It uses medium size terrain maps, normally tens of meters. It focus on detecting geometric hazards(e.g., rocks, ditches, cliffs), accounting for the vehicle's static and dynamic stability, avoiding steep slopes, bumpy regions, statically unstable due to sliding and tip over.
- Local-level path: the on-board software uses stereo images from hazard avoidance camera, identifies obstacles and computes a safe traverse path between two waypoints from Global Path Planner. It range several meters. In most cases, the ground transmits the waypoints and speed to the rover, the rover drive several meters then stop, understand the terrain into which it has driven, plan local path then move again, repeat the cycle until the last waypoint.

Robotic Arm Planner computes the angle and sequence of robotic arm three joints to against the target. Targets by selecting pixels in stereo images designate specific placement and pointing of vehicle and its science instrument. According to analyze the structural characteristic and kinematical constraint, the forward and inverse kinematical equations of 3 degree-of freedom are developed, the Denavit-Hartenberg(D-H) parameter are set. It helps to realize the following functions:

- Verify the target reachable or not in the current position and attitude of the rover.
- If reachable, find a safety path from the start point to the target point of the rover that is the angle and sequence of three joints.
- If no, set a new target or provide the new position and attitude of the rover.

Validation system provides a virtual surrounding to verify the correctness of the results from Mission Planning, Global Path Planner and Robotic Arm Planner. The command sequence will be transmitted only after all the results past the validation system. In some cases, not only the digital validation system in BACC but also the indoor test facilities in project team will be used. It receives inputs from Mission Planning, Global Path Planner and Robotic Arm Planner, ingests and merges DEM and DOM, integrates the whole dynamics of the multi-body system and complex interactions with terrain, simulates rover behavior on lunar surface with a high degree of realism, helps operators get the direct impressions on how it works in advance.

Conclusion

This paper has provided an overview of ground operations to meet the challenges and demands of China's first lunar rover .While integration and tests continue, initial results indicate the correctness. The control system will continue to evolve as the mission approaches the launch date.

References

[1]   Bresina J L, Morris P H. Mission operations planning: beyond MAPGEN[C]// Second IEEE International Conference on Space Mission Challenges for Information Technology, Pasadena Conference Center, Pasadena, California, July 17-20, 2006: 151-156.

[2]   Knight S. Casper: space exploration through continuous planning[J]. IEEE Intelligent Systems, 2001, 16(5): 70-75.

[3]   Tompkins P, Stentz A, Wettergreen D. Mission-level path planning and re-planning for rover exploration[J]. Robotics and Autonomous Systems, 2006, 54(2): 174-183.

[4]   Elachi C. Local lunar topography from the Apollo 17 ALSE radar imagery and altimetry[J]. Earth, Moon, and Planets, 1976, 15(1): 119-131.

[5]   Cook A. Lunar topography and basins mapped using a clementine stereo digital elevation model[C]// 33rd Annual Lunar and Planetary Science Conference, Houston, Texas, March 11-15, 2002: 313-318.

[6]   Cornor H F. Development of a lunar surface model for the Apollo 15landing site - case 310[R]. 1971.

[7]   NASA Marshall Space Flight Center. Lunar Surface Models NASA space vehicle design criteria environment[R]. Huntsville: NASA, May, 1969.

[8]   张伍, 党兆龙, 贾阳. 月面数字地形构造方法研究[J]. 航天器环境工程, 2008, 25(4): 35-40.
     Zhang Wu, Dang Zhaolong, Jia Yang. Research on digital lunar terrain construction[J]. Spacecraft Environment Engineering, 2008, 25(4): 35-40.(in Chinese)

[9]   陈楠, 王钦敏, 汤国安. 自 DEM 由不同算法提取坡度的对比分析[J]. 测绘工程, 2006, 15(1): 10-13.
     Chen Nan, Wang Qinmin, Tang Guoan. A contrast analysis of slopes extracted by different algorithms based on DEM[J]. Engineering of Surveying and Mapping, 2006, 15(1): 10-13.(in Chinese)

[10] 史美萍, 吴军，李焱, 等. 面向月球车路径规划的多约束环境建模方法[J]. 国防科学技术大学学报, 2006, 28(5): 108-112.
     Shi Meiping, Wu Jun, Li Yan, et al. A multi-constrained world modeling method in lunar rover path-planning[J]. Journal of National University of Defense Technology, 2006, 28(5): 108-112.(in Chinese).