An Overview of the Space Robotics Progress in China

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Abstract

At present, there are two big space exploration programs in China: China's Manned Space Engineering (CMSE) and Chang'e Lunar Exploration Project (CLEP). In both programs, the space robotics plays an important role. The China's Lunar Exploration Projects will be executed in three stages termed as orbiting, landing and returning. In the first stage, two lunar missions would be sent to an orbiter with an altitude of around 100 km in 2007 and 2010. The soft landing of Chang'e-3 in December 2013, which encompasses a lander and a rover called "Yutu" (jade rabbit), is the second stage of CLEP. In the third stage, an autonomic sampling & returning lander will be launched and soft-landed on the lunar surface to survey the landing field, collect lunar samples and return to the earth around 2020. On the other side, China's manned space station, namely Tiangong, will have been built by 2020. It consists of one core module (CM), two experimental modules (EM), and one cargo spaceship. These modules will be assembled on orbit by using a remote robot manipulator system consisting of a big arm (10m) and a small arm (5m). In this report, the current robotic progress for the CMSE and CLEP will be given in some detail. Also, some ideas about further robotic application on the Tiangong, such as a robonaut mounted on the EMM or CMM, will be discussed.

Keywords: Space Robots, Chang'e Lunar Exploration Project (CLEP), China's Manned Space Engineering (CMSE)

1 Introduction

As human deepen their sights into space exploration, development of space robotic technology seizes more and more attention in robot society. Because of the outer space's vacuum, high temperature change and intensive radiation, human astronauts working in this harsh environment take great risks, and so that extravehicular activities are extremely dangerous. At this moment, there is a large, worldwide trend in the robot community to apply versatile space robots in satellite service and space exploration. Relevant issues about on-orbit assembly and service are having been intensively investigated. Not only can these space robots substitute human astronauts for executing long-term extravehicular activities, but they can be also treated as supplementary tools for accomplishing reliable, precise operational tasks. Comparing with the human beings, the robots can resist extreme temperature and space radiation that makes complicated, expensive life support and rescue system unnecessary anymore.

The space robot is a type of special robots that are applied outside the earth circle. According to different application scenarios, the space robots can be commonly classified into three categories as extra-/inner-vehicle robots, planet exploration robots, and the freely-flying robots. The inner-vehicular robots are characterized as low weight, compact volume, sufficient dexterity and adequate operation ability. Representative systems include the DLR's ROTEX system [1] and the NASA's robonaut systems [2-4]. The extra-vehicular robots are mainly employed in on-orbit service such as those for small size satellite, space assembling & manufacturing, and experimental assistance of science payloads, etc. Typical extravehicular robots include the Shuttle Remote Manipulator System (SRMS)[5], the Mobile Servicing System (MSS) [6-7], Japanese Experiment Module Remote Manipulator System (JEMRMS)[8] and European Space Agency (ESA)'s European Robot Arm (ERA)[9-11] (MSS and JEMRMS have been servicing on the International Space Station, ISS). The planet exploration robots (PER) are used to accomplish exploration tasks on the surface of a planet or the moon, as geomorphic observation, component analysis, and sample collection. The PER should have much more autonomy that can independently accomplish various tasks without much interventions from the earth ground. Systems such as the robot twins on Mars (Spirit, MER-A and Opportunity, MER-B), recently launched Curiosity Rover, are all PER's. Freely-flying robots are those systems that fly in specific orbit around the planet, which are generally equipped with robot manipulators, for on-orbit maintaining and service for the other satellites.

Representive systems include the Orbital Express[12], ETS-VII [13], and the ConeXpress Orbital Recovery System (ConeXpress ORS)[14-15.

In China, early robot research for space exploration started from 90's. Intensive investigation of space robot was initiated from 2000 and a great number of special funds were assigned on the space robot projects. In this paper, after briefing the China's Manned Space Engineering (CMSE) and the Change Lunar Exploration Project (CLEP), we elaborate to present the current developing status of the Chinese Space Station Remote Manipulator System (CSSRMS) and the Yutu Rover, as well as to give prospective about the China's space robot development in the future, especially, for a robot astronaut.

2. China's Manned Space Engineering Project

The goal of the CMSE is to build a large-scale national space laboratory with long-term human participation. As a serial of technologies of astronaut spacewalk, manned/unmanned docking, and space transportation have been broken through, the core module and experimental modules will be soon launched for constructing Chinese space station.

The CMSE will be implemented in two stages as space laboratory and space station[16]. It aims to develop and launch space laboratory, grasp key technologies including medium-term residency, and develop certain scale of space application prior to 2016. It is also predicted to develop and launch the core module and experimental module to assemble a manned space station on orbit, master construction and manipulation technology of near-earth space station assembly, near-earth space long-term manned flight technology, and carry out large-scale space application around 2020.

The China's Manned Space Station is composed of five fundamental modules: Core Module (Tianhe), Experimental Module I (Wentian), Experimental Module II (Xuntian), Manned Spaceship (Shenzhou), and Cargo Spaceship (Tianzhou), as shown in Fig.1. Each aircraft is an independent module that can fly independently. The last four modules can also be assembled with the core module to form various types of space assembly and thus work collaboratively under a uniform schedule. In construction of the space station, it is necessary to launch the core module at first, complete platform tests and relevant task support technical identification after entering the orbit; then launch the experimental modules I and II to dock with the core module so as to form the space station. During on-orbit manipulation of the space station, the manned spacecraft will provide crew transport, while the cargo spacecraft will provide supply support.

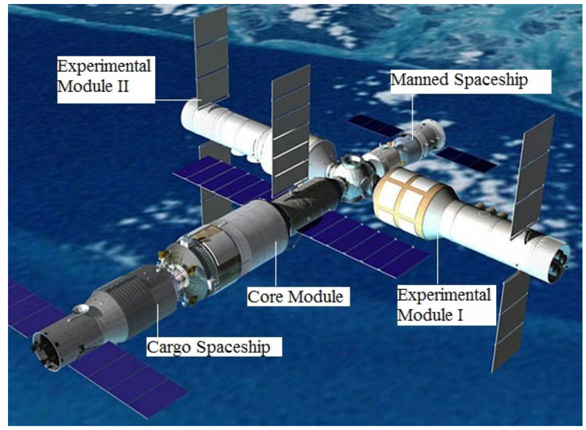

Figure 1: The Chinese Space Station under construction[1]

3. Chinese Space Station Remote Manipulator System (CSSRMS)

The robot manipulator system is an important tool in completing space tasks such as on-orbit assembly, maintenance, manipulation assistance, payload care and astronaut on-orbit support. The application of robot manipulator is beneficial to extend service life of the space station and payload, and further reduce astronaut extra vehicular risk to obtain more scientific and economic returns.

From the view of the successful application of Canada and Japanese manipulators in the ISS, it is found that these space robots primarily have the following technical characteristics:

- Cooperative work of two manipulators
- Ability of crawl moving
- High-tolerance capturing ability
- Modular design of core parts
- Necessary safety consideration

It has been well noticed that the single manipulator is hard to independently complete various operating tasks on the space station. Thus, mutual manipulation and collaborative work of manipulators with different sizes and functions are necessary.

The space manipulator needs to complete tasks as module transposition, full-range payload care, astronaut EVA activities, outside check of the module, and equipment transportation and installation. The experimental payload primarily includes exposed experimental platform on experimental module I and optical platform on experimental module II. In this large range (about 17m), taking care of all payloads requires the manipulator has long length and high end precision. In consideration of launching power, space limitation and end operating task, the China space station manipulator was configured as a dual-arm setting (10m+5m): the big manipulator completes the manipulation with heavy payload and relatively low accuracy requirement in broad range; while the small manipulator completes the manipulation with high accuracy in narrow operating space. The big manipulator is installed to the space station core module (termed as core module manipulator, CMM); and the small manipulator is located to the experimental modules I or II (termed as experimental module manipulator, EMM) and able to be transferred between these two modules with the assistance of the big manipulator.

Functions of the big manipulator are primarily to transpose module, care payload of core module, carry cargo, and assist the small manipulator for conducting astronaut EVA activities in the range of all modules. The small manipulator is able to work independently on the experimental module I and II, so as to look after the exposed experimental platform and optical platform, module check and EVA activity support, as shown in Fig. 2.

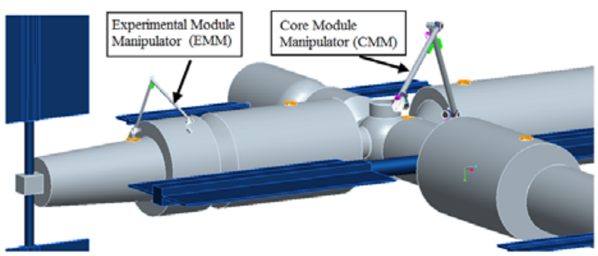

Figure 2: CMM and EMM independently working on experimental module

Another feasible configuration is that the small manipulator is located to the end of the big manipulator to compose a series-connected manipulator system with length of 15m, as shown in Fig. 3.In accordance with the required operation tasks, we provide some core specifications for the China space station manipulator, as shown in Table 1.

The EMM is a 7-DOF robot arm system, wherein its 2 wrist parts have total 6 DOF's (each has 3 DOF's) and the elbow joint has 1 DOF. Both ends of the EMM are installed with an end-effector, respectively, which is configured with hand eye cameras and elbow cameras.

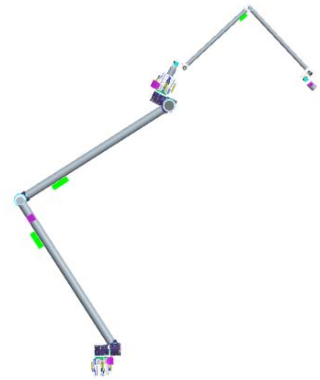

Figure 3: CMM and EMM series connection

Table 1 Specifications of the CSSRMS

Work capacity (in effective work space)		EMM	CMM
1. Base fixed type maximum working radius (m)		5	10
2. Maximum movable mass (Kg)		3,000	25,000
3. Maximum moving speed of the end	Translation (m/s)		
	- No load	0.200	0.300
	- Full load	0.030	0.020
	Orientation (deg/s)		
	- No load	3.0	3.0
	- Full load	0.15	0.15
4. Maximum moving acceleration of the end	Translation (m/s^2)		
	- No load	0.010	0.010
	-Full load	0.002	0.001
	Orientation (deg/s^2)		
	- No load	0.45	0.2
	-Full load	0.15	0.1
6. Maximum end absolute positional accuracy (mm)		±10	±45
7. Maximum end repetitive positional accuracy (mm)		±3	±15
8. Maximum end absolute posture accuracy (°)		±1	±1
9. Maximum end repetitive posture accuracy (°)		±0.5	±0.5
10. Maximum end applied force			
-continuous (N), time of duration greater than or equals to 30s		50	200
-peak value (N), time of duration less than or equals to 3s		75	400
11. Maximum end applied torque			
-continuous (N.m), time of duration greater than or equals to 30s		15	500
-peak value (N.m), time of duration less than or equals to 3s		30	800
12. Maximum full load braking distance (m)		0.15	0.5

One end-effector is used for connection between the small manipulator and the experimental module as the work base; the other end-effector is used as the tool for payload operation and can be also used for docking with the CMM to compose a longer series-connected manipulator. The controller is placed on the main body of the CMM and moves with it. The whole configuration of the small manipulator (EMM) is shown in Fig 4.

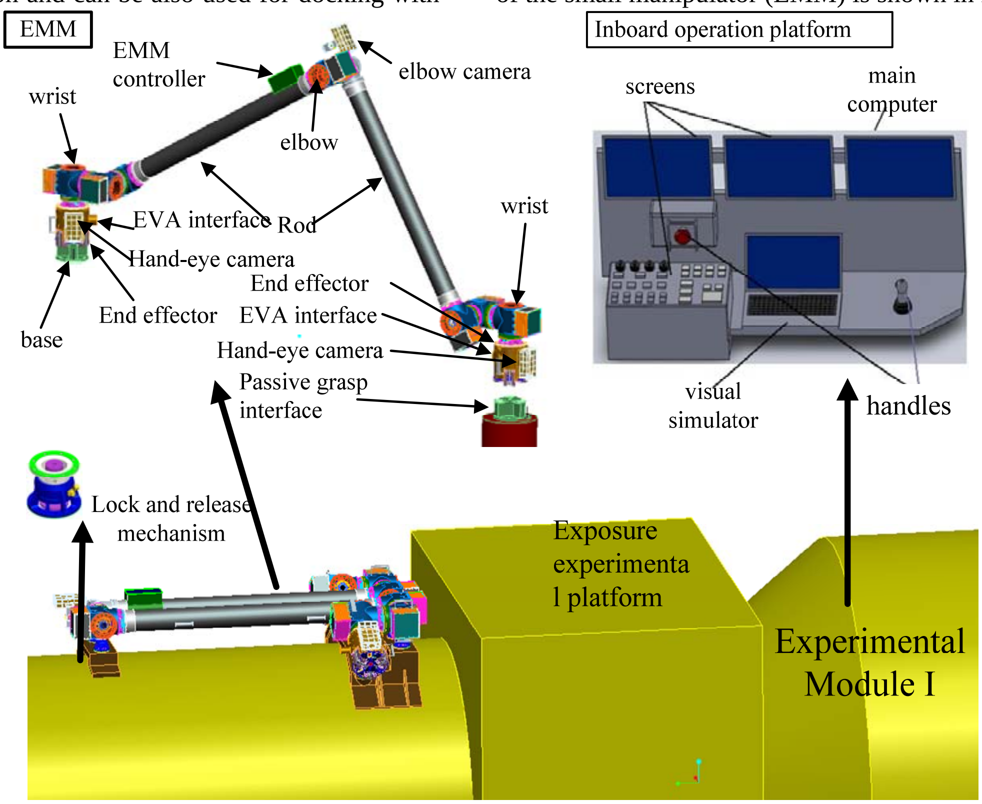

Figure 4: CMM Configuration

The EMM joint consists of a brushless DC motor and a harmonic reducer. The end-effector is a type of three-jaw gripper with great capture tolerance, realizing functions of capturing, locking and electric connection. This end-effector also realizes power output to other end operating tools and ORU replacement unit. Meanwhile, the end-effector is provided with a foot supporter and astronaut control switch which supports EVA manipulation. The hand-eye camera is mounted on the end-effector for object measurement; another two cameras at the elbow joint for monitoring status of manipulators, astronauts and work place in a broad range. The whole control scheme is constructed as two layers. In the top layer, the small manipulator controller serves as manipulator's motion trajectory planning. While in the bottom layer, the lower computer - joint and end-effector controller - realizes accurate position and torque control. The manipulator rod is made of resin-based carbon fiber material for low weight, high strength and good stability. In order to guarantee the EMM to be firmly and reliably fixed and to avoid damage in the launching phase, a multi-point locking-releasing mechanism is developed, with its finite element analysis being conducted based on the launching conditions.

4. China's Lunar Exploration Project

After a 10-years' discussion, the China's project for lunar exploration was formally started in 2004, namely Chang'e lunar exploration project (CLEP). The CLEP is carried out after the nation having dominated such key skills as aircraft manufacturing, lunching and operating. The concrete implementation of the CLEP will be split into 3 engineering phases: orbiting, landing, and returning[17].

The first phase orbiting (2002~2005 or later) was to investigate and launch a lunar exploration satellite that can apply global, integral, and systematic measurement to the distribution of potential lunar energy and sources as well as conduct detection to the Moon's geomorphy, topography, geological structure and physical field. Currently, the second phase landing (2005～2010 or later) is to accomplish robot probe's soft-landing and on-moon exploration. Robot lander and automatic rover should be developed and lunched in this phase. The third engineering phase returning (2010～2020) hopes to conduct more deep exploration on the moon and return the samples from the moon.

In 2007, the Chang'e 1 satellite completed the observation tasks to the moon's surficial environment, geomorphy, topography, geological structure and physical fields, which showed a complete success of the first-phase CLEP. In 2008, after promoting the backup Chang'e 1 satellite, the Chang'e 2 satellite was developed and launched as a pilot satellite for the second phase of CLEP. On 14th December of 2013, the Chang'e 3, which contains a soft-lander and the Yutu Rover, successfully landed on the scheduled site of the moon, meaning that many significant technologies such as soft-landing, on-moon cruising, and lunar night maintenance have been well mastered.

5. Yutu Rover (jade rabbit)

The early research work about lunar exploration robot in China can be back to 2002. After 10-years persistent efforts, the final fashion of the lunar rover named Yutu (jade rabbit, a name of a pet rabbit owning by Chang'e who is a goddess living on the moon according to a traditional Chinese legend) was carried out in 2013. The main missions of Yutu are to observe the moon's topography and geology construction, to explore the components of its surface materials and resources, and to measure the physical characteristics of the lunar soil, etc. It is the first time that China completes a soft-landing on the moon, when the Chang'e 3 detector landing on the Rainbow Bay. When Yutu Rover was "walking" on the moonland from the lander (Fig. 5), it is well recognized that there has no artificial vehicle landing on the moon for nearly 40 years. Mutually photographing (Fig. 6) between the lander and the Yutu Rover shows that the Chang'e 3 launching mission is completely successful.

The Yutu Rover is an unmaned robot vehicle. It is box-like of 1.5m length, 1m wide and 1.1m height. It weighs 136 kg with 6 wheels, two foldable solar battery panels, a remote communication antenna, cameras for navigation and avoiding obstacles equipping on the top, front and back of the vehicle, a mechanical robot arm. The detailed structure is shown in Fig.7.

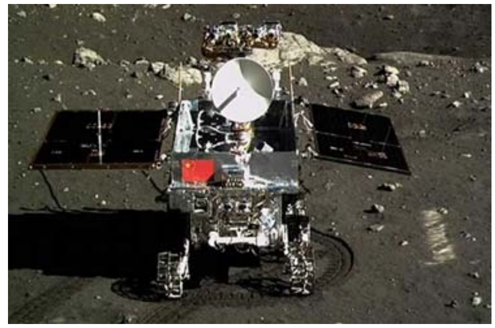

Figure 5: Yutu Rover landing on the moon

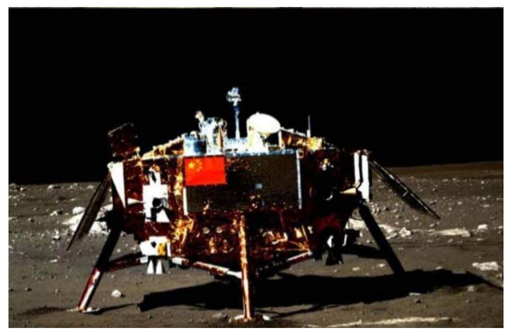

Figure 6: Photo of Lander taking from Yutu

The Yutu rover has a rocker suspension configuration and a wheel-type walking apparatus, which is independently actuated. The 3-D vision is employed for recognizing its surrounding environment, based on which a safe path planning was implemented.

There is a 3-DOF robot arm (Yutu hand) equipped on the Yutu Rover. Under precision control from the earth ground, the robot arm can help accomplish scientific exploration to the lunar soil. In the first exploration process performed by the Yutu's hand, the end optical instrument which emitted X-ray was nearly 20mm apart from the object, and the whole process lasted for nearly 30 minutes, which shows a superior precision and reliability.

Before the second lunar night hibernation, a fatal malfunction of mechanical control appeared. Although making urgent repair attempts, the staffs implied that the malfunction would not be properly fixed and the Yutu cannot make it after the noon night. At the time of

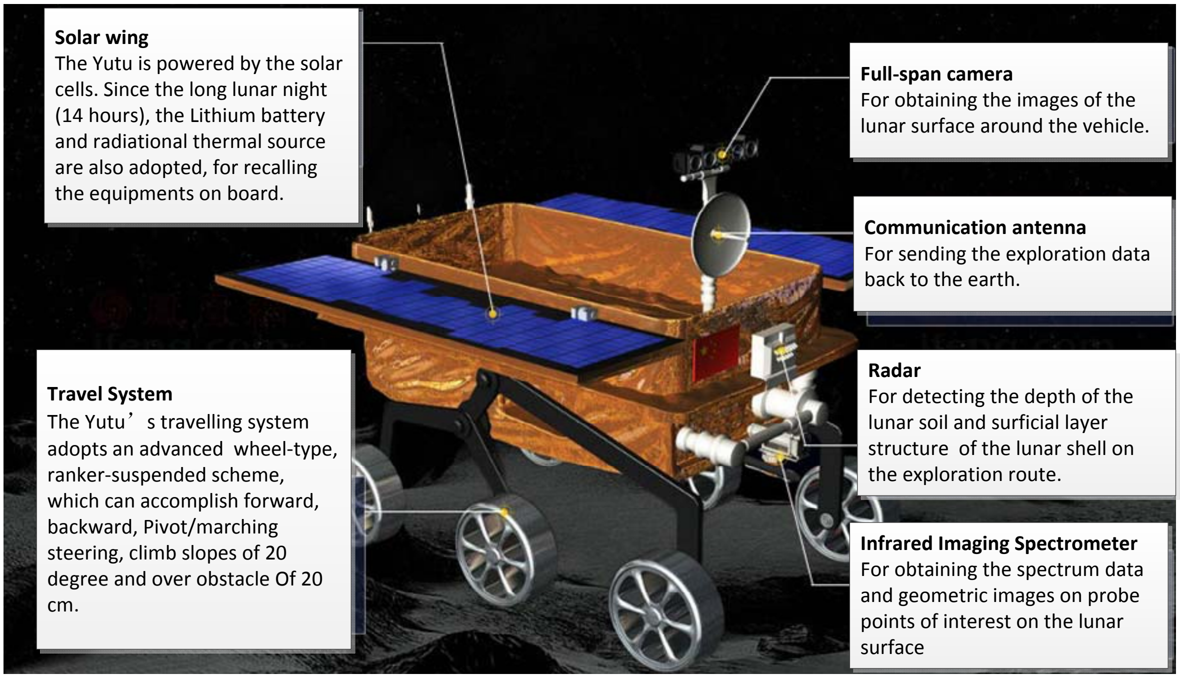

Figure 7: System composition of the China's Yutu Rover

writing, a source from CELP said that the Yutu Rover has recovered to the status before hibernation. After analyzing the data transferred back by the on-ground application system, the full-range camera, moon sight radar, and the infrared imaging spectrum instrument are still in normal status. The malfunction of the mechanical system might attribute to the raising lunar dust when Yutu is walking [18].

6. Prospect of the space robots in China

Robot manipulators can be used to largely reduce extra vehicular work amount for the astronaut. However, some fine manipulations, such as maintenance and interchange, still need the astronaut to participate. When performing extra vehicular activities, the astronaut must wear extra vehicular space suits to protect himself/herself due to the huge risk of space environment. Attribute to the space suit's high weight, poor mobility and long preparing time, it is not appreciated in some circumstances that need fast response and rush repairs.

Benefited from the development of robot technology, the robot astronaut is able to take the place of, or assist, the astronaut to transport, inspect and operate in and out of the space station. The robot astronaut has the superior advantage on long-term unattended space stations (or space laboratories), extra vehicular or exposed experimental platforms. It could assist the astronaut to complete time-consuming and boring scientific experiments with tedious operating process; also, it can cooperate with the CMM or EMM as an extension of manipulator arm function out of the module to realize assembly and construction work.

A prototype of a robot astronaut has been developed, as shown in Fig. 8. One idea is to take the robot astronaut as an intelligent agent to the end of the space station manipulator to reduce the space activity risk cost. The space station manipulator is used to help the robot astronaut instead of human being, accomplish a broad range movement, go out of the module and complete fine and dexterous manipulation.

Currently, several key technologies relating to the robot astronaut has been brocken through, including 1) highly-integrated flexible manipulator joint [19], 2) modular and multi-sensory dexterous hand fingers[20], 3) cooperative control technology with dual-arm dual-hand, 4) embedded microprocessor based binocular target tracking technology, 5) telepresence remote manipulation technology with touch feedback [21]. It is expected to combine with the experimental module manipulators to further develop space manipulation task ground verification tests.

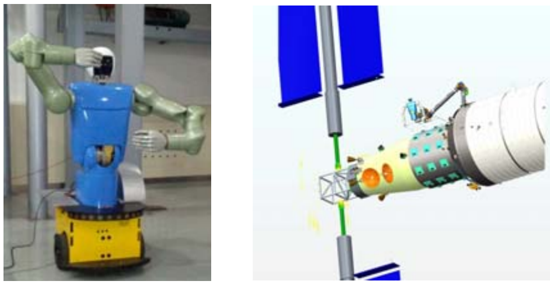

Figure 8: Robot astronaut prototype and possible use

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