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A Survey of Lunar Cranes and Some Inspiration from the Perspective of Earth Crane Technology

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***Abstract*— Since the end of Project Apollo, no such large lunar exploration projects have been carried out. However, much research and many investigations have been carried out in order to analyze and propose detailed human exploration of the Moon in the future. From the results of completed studies, the next generation of lunar exploration should be diverse missions with complex functional compartments and long-term personal station. For the demands of such large construction works, professional equipment is inevitably needed. Based on the experience of construction on Earth, the concept of developing a kind of crane system for lunar missions was firstly proposed in the 1980s. More detailed designs using the concepts of the gantry crane and the boom crane with stable hoisting systems were established in the 1990s. In the first decade of 21th century, a device called the Lunar Surface Manipulation System (LSMS) was presented with two generations of prototypes, along with two variant models. The LSMS is designed with similar structure and features to a lattice boom crane on Earth, and such similarities bring us great inspirations from the current and the upcoming technology of Earth cranes. For example, the optimization of the cable-boom folding structure and mechanism involves to the lattice boom cranes, expanding the operation range by considering a telescopic boom system.**

I. Introduction

Over these first twenty years of 21st century, a new peak in lunar exploration has arrived. During this time, the exploration of the Moon has no longer been a competition with predominantly political considerations, but an international cooperative activity for the purpose of scientific and sustainable development. In 2004, the first European Moon mission, SMART-1, reached the orbit of Moon and accomplished its mission successfully. The second lunar exploration mission of Japan, SELENE, was launched in 2007 to study the origin and the evolution of the Moon.[1] In the same year, the first Chinese lunar orbiter, Chang'e-1, was launched in Xichang with a Long March 3A carrier rocket, as the first lunar probe of Chinese Lunar Exploration Program (CLEP).[2] The first Indian unmanned lunar probe, Chandrayaan-1, was launched in 2008. Some new views on lunar science, including OH/H_2O, spinel, polar ice and uncollapsed lava tubes, were provided by the payloads on Chandrayaan-1.[1] After some modification, the backup probe of Chang'e-1, Chang'e-2, was launched in 2010. One of the major goals of Chang'e-2 was to obtain high-resolution images of several selected regions as a potential landing site for robot or human landed missions in the future.[3] After the accomplished lunar mission, Chang'e-2 made a journey through the Sun-Earth Lagrange point and a successful flypass of the near-Earth asteroid 4179 on 13 December 2013.[4] As the second phase of CLEP, Chang'e-3 has successfully landed on the Moon with the Yutu rover, in order to conduct scientific activities of lunar geology, earth's plasma sphere and moon-based astronomy.[5] It makes China the third country to achieve a landed exploration on the Moon independently.[6] Recently, after being upgraded, Chang'e-4 (which was designed as the backup probe for Chang'e-3), landed on the far side of the Moon on 3 January 2019 with the help of a relay satellite Queqiao near the second Earth-Moon Lagrange point.[7][8] Besides the Yutu-2 rover, eight scientific payloads are being carried by Chang'e-4, including the Lunar Lander Neutrons & Dosimetry experiment (LND) from Germany and the Advanced Small Analyzer for Neutrals (ASAN) from Sweden. In addition, the Netherlands-China Low-Frequency Explorer is being carried by the relay communication satellite.[9]

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Even though many countries have made great progress on their lunar exploration missions, the USA still holds the leading position, and will not give it up easily. On 11 December 2017, the "New Space Policy Directive Calls for Human Expansion Across Solar System" was signed, which called for the NASA administrator to "lead an innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the solar system and to bring back to Earth new knowledge and opportunities".[10] Furthermore, an exact time point has been given recently in an official policy of the USA to return astronauts to the surface of the Moon by 2024[11], fifty-two years after Apollo 17's departure. Long-term and continuous research and development achievements are prerequisites for the USA to draw up such a clear timetable. The Lunar Reconnaissance Orbiter/Lunar Crater Observation and Sensing Satellite (LRO/LCROSS) were deployed in 2009 to search for ice in the permanently shaded crater near the Moon's south pole.[1] Grains of mostly pure ice were picked up by LCROSS after the impact of Centaur stage; it confirmed the presence of water in the regolith of the impact site.[12] In addition, the Gravity Recovery and Interior Laboratory (GRAIL) arrived the orbiter in 2012 and revealed features of internal lunar structures by mapping the gravitational field of the Moon.[13] The Lunar Atmosphere and Dust Environment Explorer (LADEE) was launched in 2013, and by mapping the size and spatial distributions of dust grains on the Moon, it noted two possible dust sources as the small grains due to the bombardment of micrometeoroids on the Moon and plasma-induced near-surface electric fields.[14] These probes mentioned above are still active and functional. The LRO even took an orbiter picture of Chang'e-4 and Yuto-2 rover when it

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flew over the landing site near the Von Kármán Crater.[15] A clear plan for human return to the Moon has been put forward by NASA. A habitable space station called the "Lunar Orbiting Platform-Gateway (LOP-G or Gateway)" is planned to be deployed at the Earth-Moon L2 Lagrange point above the far side[16] or on a near rectilinear halo orbit[17]. The Gateway will allow long-term stays and may in the future be used as a transfer station for the lunar surface missions. Astronauts and scientists can control the tele-robotics from the Gateway, and the designed docking station also offers astronauts access to both the near and far sides of the lunar surface.[18]

Currently, there is no clear time schedule for China's manned lunar exploration plan. The third phase of CLEP will commence around the end of 2019, with Chang'e-5, which will land on the Moon and bring lunar regolith samples back to Earth.[19] After CLEP, continuous lunar exploration missions should be carried out. The tasks should include deeper scientific exploration, the establishment of long-term unmanned research station and the preparation mission for an astronaut landing. An initial plan was proposed to launch three to five robotic landers carrying a dozen robotic rovers, to accomplish the unmanned exploration stage before 2030.[8]

Whether the USA's plan to return astronauts to the Moon, or China's unmanned lunar mission, it is certain that a new phase in lunar exploration has come. Without much political influence, the next generation of lunar exploration will be conducted with the consideration of sustainability and efficiency. Besides landers and rovers with scientific payloads, some large manipulators capable of heavy tasks are also needed to meet the growing scale of the lunar mission. Such equipment is necessary for cargo offloading and lunar base construction, which is evidently difficult for astronauts to do manually. A straightforward idea to solve this problem is to find such devices on the Earth which carry out heavy tasks and "transport" them on the Moon.

Figure 1. A typical crawler crane and a fast-eracting tower crane (Citation: Liebherr)

Using cranes for the exploration of the Moon is no longer a novel idea. During the decade after the Apollo missions, many investigations were undertaken to depict the returning to the Moon, and in these reports, the use of a lunar crane system was mentioned.[20][21] In addition, some possible designs of manipulator[22] and some consideration of details[23] were presented in the 1980s. After that, based on certain types of Earth cranes, some possible prototype designs were discussed, such as gantry cranes and boom cranes.[24][26] The interesting aspect is that the current successful design of lunar crane has a very similar structure and mechanism as those from crawler cranes and tower-erecting cranes on Earth. We will expand on this description in the following chapters.

II. Research in the 1990s

A. *Lunar construction cranes*

In order to unload the cargo (such as a lunar vehicle or habitation) from the lunar landing platform, and to control all the degrees of freedom, several crane designs were proposed around 1990. The concept of a gantry crane, Lunar Excursion Vehicle Payload Unloader, or LEVPU, was mentioned in the relevant NASA reports.[21][24] This moveable gantry crane has three telescopic legs for leveling and elevating an overhead platform which can control the payload with six DOFs. The powered wheels are mounted on each leg to provide mobility, as shown in [21, Fig. 2]. For gantry cranes, tipping is not a problem because the crane straddles above the payload. Boeing and the National Institute of Standards and Technology (NIST) also have similar designs, as shown in [25, Fig. 2]. NIST provided a design of a suspension system using six cables and each of them was driven by a winch individually. This crane was named the NIST SPIDER and this overhead gantry crane for lunar construction is similar to the LEVPU.[25]

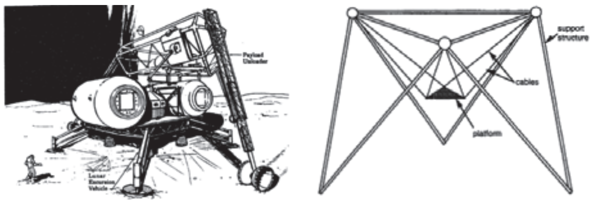

Figure 2. Lunar Excursion Vehicle Payload Unloader[21] (left) and NIST SPIDER geometry[25]

The designs of gantry crane were considered in the earliest stage perhaps because this kind of cranes can use self-weight to avoid tipping without counterweight. However, a large self-weight also leads to a large crane-to-payload mass-ratio and it is inefficient. For the lunar surface operation, the boom crane can use lunar soil or rocks as counterweight. Besides, the boom crane can cover larger operation area without moving itself.

The typical mobile crane on Earth uses its boom system with a single cable (or pulley block) to lift the payload, but this simple pendulum system makes accurate positioning difficult. This is a major shortcoming of the boom crane, and which could be overcome with a design similar to the NIST SPIDER. A conceptual design of a cable suspension was presented which controls over all six DOFs of the payload. The design only uses a single lifting winch to drive two cables passing through pulleys to form a stable suspension structure with six links connecting the boom and the payload.[26]

III. Lunar Surface Manipulation System

NASA has already designed and built a test-bad system for the tasks of lunar surface construction, called the "Lunar Surface Manipulation System (LSMS)", as shown in [28, Fig. 3]. It seems that NASA referenced the typical boom crane system during the conceptual design stage, and the subsequent

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prototype-design stage. In this chapter we will focus on the introduction of the LSMS.

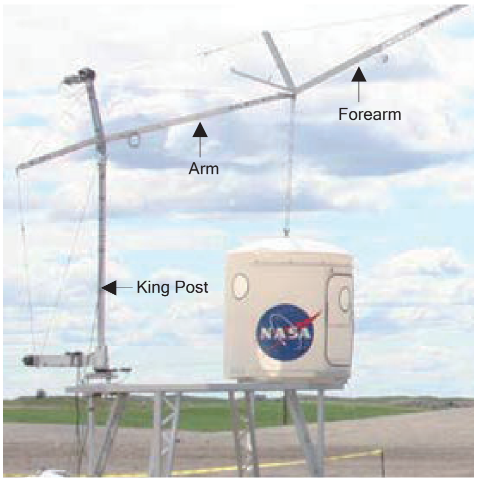

Figure 3. First generation LSMS in the field test (offload large air lock mockup)[28]

A. *Features of the lunar construction and LSMS*

In past lunar missions, a key observation was that very little work had been undertaken for the class of payloads which were larger than the capacity of the crews. One conclusion was given by the study "Lunar Surface Construction & Assembly Equipment Study" (Eagle Engineering, 1988) was that the major construction tasks most likely to occur during lunar base construction were: 1) unloading cargo from lunar landers, 2) transporting loads, 3) lifting and positioning loads, 4) preparing the lunar surface for a base site, landing pads and roads, 5) providing quantities of lunar soil for habitat radiation protection and 6) assembling large structures.[27] To be precise, the lunar payload can be mainly classified into three types: 1) hardware and supplies prepacked on the landers, 2) sensor packages for lunar surface investigation, 3) lunar materials, such as lunar regolith or rocks.[28] The first two types of payloads are needed to be off-loaded from the landers and the third type requires excavation or drilling devices. Although there are several types of Earth base construction equipment, these devices lack the necessary properties for space transportation and the harsh working conditions on the lunar surface.

The key features of the LSMS are implemented with the goals and the particularity of a lunar construction mission in mind. Besides the characteristics of versatility, modularity, mechanical simplicity and reliability, some desirable features are as below:

- lightweight, with compact packaging design for launch;
- large operation range to cover the mission requirement and the ability to load or unload payloads horizontally,
- multi-segment articulated boom with single degree of freedom along the boom;
- variable number of spreaders at joints which are designed to optimize the complex geometries of boom for unfolding and lifting;
- modularity design for boom structure and variable boom configuration for different task requirements;
- fewer pulleys (to minimize rotating components) improving robustness against the harsh lunar dust environment;
- isolation and distribution of the actuation elements, which enables the actuators to be completely enclosed, to protect against the harsh lunar environment, and to facilitate rapid upgrade and periodic replacement;
- non-collocated joints and actuators, crane like, which significantly reduces the weight.[27]

B. *First generation LSMS*

The first generation LSMS was built and tested by NASA in 2008. The LSMS design uses the conventional cable-suspended boom system which is broadly achieved through typical lattice boom cranes, the names of the components are shown in [28, Fig. 4]. Due to the needs for precise positioning, the operation of the LSMS also involves as a manipulator.

In the consideration of structural efficiency, the end part of the forearm boom is designed as a lattice structure to reduce the weight. The approximated weight of the LSMS is estimated as 3% of the maximum lifting mass at the tip of forearm. The actuators are arranged such that they are offset with regard to the joint, using tension cable to support the structure and to control the deployment sequence. The design also includes a lifting link to hoist the payload. Compared to a traditional hoisting rope, the lifting link can provide sufficient rotational stiffness. A fork-lift end effector can be mounted when the boom system is set to its fork-lift configuration, for accessing the payloads under the lander deck. The mobility of the LSMS was also considered in the self-offloading design; the LSMS can re-position itself on the lunar vehicle.[28]

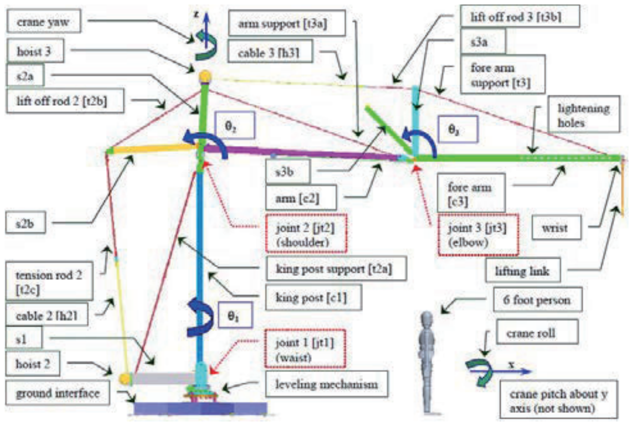

Figure 4. 1st generation LSMS[28]

C. *Extension of the first generation LSMS*

Based on the first generation LSMS as a test bed, the researchers expanded the versatility and the autonomy of the LSMS, for example through changes in the design and development of tools and end effectors:[31]

1) New design for shoulder joint and its spreaders which increase the manipulator's range of motion, the additional third spreader increases the rotation range of the join, the offset fingers improve the stiffness of the joint, and the kingpost is able to tilt forward.

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2) A tilt mechanism is mounted on the wrist, it provides one more rotational DOF at the wrist and increases the agility for the tools and end effectors.

3) Tool quick change device at the wrist increases the versatility. The quick change device allows the LSMS to change grippers, tools or instruments without the assistant from the astronauts. Dust-tolerant features are also considered to prevent the damage from the harsh environment like lunar dust.

4) Various end effectors which include: lifting link (fixed length or variable length), gripper, pallet operations and digging operations, welding (shown in video).

5) Vision and tracking system, remote operations, software development. These developments are essential for the autonomous operation in the future, including path following, targets and obstacle identification and some necessary remote control.

The forward and inverse kinematics of the LSMS was also analyzed, and some improved control technologies were used to optimize the operation maneuver.[32]

D. Second generation LSMS

The main goals of the 2nd design are to include the self-offloading ability (will be explained in section E) and to optimize the design of the structures and components. These lead to the designs for two essential mechanical components: lightweight boom structure and lightweight waist joint.

How to reduce the total weight of the LSMS is one important objective for the development of the second generation. Some researchers have investigated the manipulators for lunar and Mars planetary surface applications from the aspects of mass and size, by considering possible structural configurations including cantilevered boom and cable-boom configurations with tubular or lattice boom structures.[33] It gives the specific conclusion that a cable-boom manipulator configuration has impressive advantages compared with a cantilevered boom manipulator. For a certain maximal lifting capacity, the mass of the cable-lattice-boom design is about 50% less than the mass of cable-tubular-boom design and about 85% less than the mass of a cantilevered boom manipulator.[33]

A quite heavy (38.5kg) turntable bearing was used at the waist joint in the design of the 1st generation LSMS. It can influent the self-offloading process significantly as a large concentrated mass, not even considering the additional special-designed grapple mechanism. A design for a cable-drive joint is described in [31] to make a lighter waist joint. Compared with the waist joint on the 1st generation LSMS, the improvements in this respect are: 1) the overall size is smaller; 2) the main structure is made of aluminum (instead of steel); 3) using cable drive to replace the worm drive; 4) reduce the self-weight by eliminating a lot of fasteners; 5) using a single nut to preload the bearing.[29] The electric motors drive cables to control the shoulder and elbow joints and another motor controls the rotational DOF of the waist.[32]

The overall structure and mechanical design of the 2nd generation LSMS has following minor modifications compared with 1st generation:

1) The cable actuator that controls the elbow joint was moved to the power spreader with the other cable actuator for shoulder joint in order to optimize its self-loading configuration. [29]

2) The arm-support cable was divided into two separate lines to prevent cable contact.

3) An additional motor is mounted at the bottom of the king post to make it possible to lean forward, to increase the operation range and to support the reaction force during the shovel operation.[31]

4) All motors are mounted at the lower parts of the LSMS. This has two advantages: it's possible to switch to manual operation when the electronic system fails and easier to repair or replace the components.

5) A special-designed grapple mechanism which includes three electrically driven studs are used to support automated self-offloading.[31]

E. Deployment sequence and self-offloading process of 2nd generation LSMS

Generally speaking, there are four steps for the LSMS to be deployed as per [31, Fig. 5].

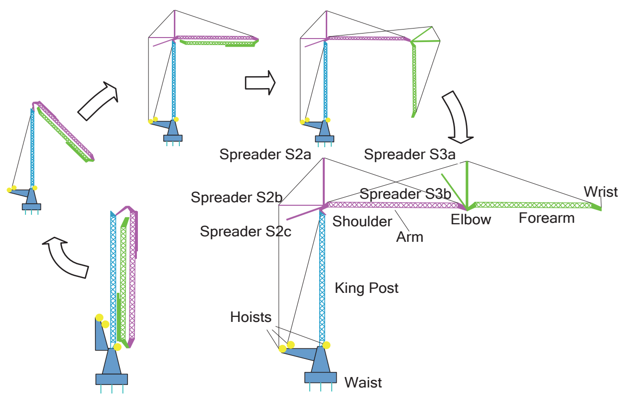
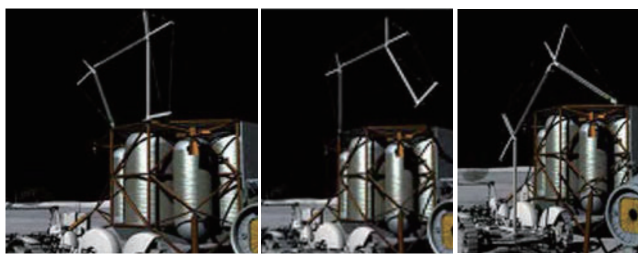


Figure 5. Deployment sequence of 2nd generation LSMS[31]

First, the power spreader (equipped with motors) deploys and locks at the operation position; next the arm is lifted by the motor and locked at the top of the king post; and then the shoulder spreaders (s2a-c) are unfolded; finally the elbow spreaders (s3a-b) and forearm are deployed.[31]



a) Wrist end-effortor grapples fixture on lander
b) Base is released
c) Base is lowered onto mobility chassis

Figure 6. Self-offloading process of the LSMS[29]

The LSMS is also designed with the ability of self-offloading. The sequence of the process is illustrated in [29, Fig. 6]. A special end-effector, special-designed grapple mechanism, is attached at the wrist of the LSMS, so that it is possible to grapple the special structure on the lander desk

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([29, Fig. 6a]); then the LSMS can release its base from the lander deck and uses the elbow and shoulder joints to elevate itself ([29, Fig. 6b]); finally by using the rotational DOF of the special-designed mechanism at the wrist, the LSMS can rotate the base over the lunar surface, and low the base on the lunar vehicle or fixed position using its elbow and shoulder joints (([29, Fig. 6c])).This ability of self-offloading gives the LSMS more flexibility and even mobility to cover larger operation range.[29]

F. Variants of the LSMS

Besides the 1st and 2nd generations of the LSMS, there are also two variants of LSMS, i.e. Single-Link LSMS and LSMS-H.

TABLE I. DIFFERENT LSMS CONFIGURATIONS[31]

Configurations	Height (m)	Radios (m)	Wrist Cap. (kg)	Device Mass (kg)	Construction Type
Generation I	3.75	7.5	1000	309	Al Tube
Generation II	4.25	8.5	3000	190	Al Lattice
Moderate Lift	3.75	7.5	4879	108	Composite
Heavy Lift	4.17	8.34	6907	169	Composite

In [31, Tab. 1] four existing configurations of the LSMS with some dimensional information are presented. The Single-Link LSMS is designed for the critical mission requirement of lifting injured astronauts from a lunar surface. It is developed based on the 2nd generation, without a forearm. A special rescuer basket for the wounded is also included. The LSMS-H is designed for heavy-lifting operations based on the 1st generation. With some modifications, its lifting capacity and radius can be expanded to fit the requirement for heavy cargo lifting (up to 12 metric tons). For this configuration, the stability or tip-over evaluation is essential for three possible offloading scenarios, mounted to Altair Lander, attached to the mobility chassis or located on the lunar surface. For the first two cases, the weight of the lander or the chassis may act as the counter weight. A tension guy support is needed for the third scenario.[34] New composite material is applied in these two variants. The self-weight is reduced along with the increase of lifting capacity.

IV. INSPIRATIONS FROM EARTH CRANES

A. The similarities between lunar cranes and Earth cranes

It is an interesting fact that NASA engineers considered the crane system for planetary missions in the future, and that they already designed and built the LSMS system which has so many similarities with an Earth crane, and in particular with the lattice boom crane. However it is also reasonable, because the purpose of this consideration is future construction work on the Moon or Mars which also involves heavy lifting operations. In addition, the boom crane has the highest ratio of capacity to self-weight, which makes it more suitable for the lunar mission.

The current lunar cranes from NASA have following points which are also essential in the design of lattice boom cranes on Earth, as per Fig. 1:

1) Strict control of self-weight and dimensions. Due to reasons of cost and mobility on the road, mobile lattice boom cranes are designed to have minimal self-weight and size.

2) Self-deployment design. Self-deployment is very important for the rapid urban scenario when there is no large space for additional auxiliary cranes.

3) Spreader and cable supporting system. This provides stable triangle structures and large erecting angles.

4) Lattice boom structure. A lattice structure is clearly a good choice for minimal weight with sufficient strength. The 2nd generation LSMS uses a lattice structure for all the boom structure.

5) Integrated arrangement for the actuators. All the motors of the 2nd generation LSMS are located on the base.

Based on a typical fast-eracting tower crane 34K from Liebherr, a schematic diagram is drafted as per Fig. 7 to illustrate an idea of mounting a reduced version of earth crane on a lunar lander. The boom system also includes three main parts as forearm, arm and kingpost. But in our design, the kingpost is a telescopic lattice boom. This advantage could increase the hoisting height, and also the operation range if the kingpost is able to lean forward. It is clear that the deployment sequence and the packed configuration are different from the LSMS.

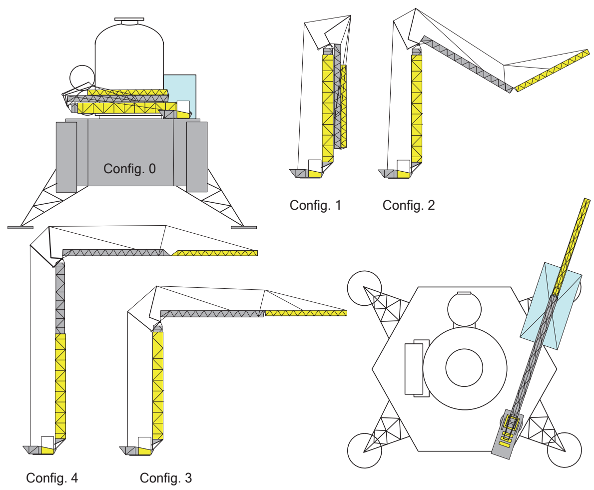

Figure 7. Earth crane on a lunar lander

B. Some improvement ideas

Based on the existing or ongoing research technologies, we would like to provide some improvement ideas for the next generation of lunar cranes:

1) Telescopic boom system. A telescopic boom system was proposed previously in [22], but was not applied – perhaps due to the complexity of the telescopic mechanism. It is still a good option for a king post or other telescopic arm, to reduce the loaded size, or conversely to increase the full erecting size.

2) Modularization design. In future lunar exploration missions, some robotic landers with smaller crane systems might be launched before manned missions. Such small cranes of a modularization design could be assembled into a larger crane for heavier operations, by rearranging lattice boom sections or by making a double-boom parallel arrangement. These technologies are already used on mobile lattice boom cranes.

3)Application of new material. According to a result of higher assumed modulus, using graphite epoxy for lattice

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structure provides about 50% mass saving compared to aluminum.[33] New composite material can provide equivalent strength with significantly smaller mass. New technologies for non-traditional machining and manufacturing composite material to build lighter components and structure should be investigated. The mechanics analysis of such composite structure should also be analyzed to ensure the structure strength and stability.

4) Intuitive control. For the tele-operation from the orbiter or onsite operation, a smarter and effective operation is always the best choice. An intuitive control strategy could make the operation easier for the astronaut, without long training times. It emphasizes man-machine interaction and could be developed based on some technologies well used by the current lunar crane, such as inverse kinematics analysis, machine vision and motion control. The intuitive control for crane system is still the subject of ongoing research.[35]

5) Structure vibration control. Even though gravity is lower on the Moon, the dynamic load from the inertia remains. A proper control strategy to minimize the structure vibration during the operation could improve efficiency and safety, such as locating the cargo more easily.

V. Conclusion

When people look back at the Apollo Project, it is always commended as a great success in human history, not only because it expanded the activity range of humans beyond Earth, but also due to the fact that the technologies developed for this project had feedback-benefits for life on Earth. Now, rational and detailed preparation tasks are needed for the next generation of lunar exploration. We believe that it is a good idea to refer some well-developed or novel technologies on Earth for the design of future planetary exploration, with some improvements. It could reduce difficulties around having a whole new design, and some particular development for strict requirement could be a technology reserve for the crane industry on the Earth.

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