Update on the Qualification of the Hakuto Micro-Rover for the Google Lunar X-Prize

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1 Introduction

1.1 Commercial off the shelf components in space robotics missions

In the past several years, due to the proliferation of cubesat and micro-satellite missions, several companies have started offering off-the-shelf space-ready hardware[3]. These products offer a welcome reduction in cost but do not solve a major problem for space robotics designers: available space-ready controllers are years behind COTS microprocessors and microcontrollers in terms of performance and power consumption. For applications involving human safety or critical timing, the extra cost and difficulty of using certified space-ready hardware is justifiable.

But for some low-cost missions that require high performance, terrestrial components are increasingly being qualified and integrated. The University of Tokyo's HODOYOSHI 3 and 4 satellites have integrated readily available COTS FPGAs and microcontrollers and protected them with safeguards against Single Event Latch-up (SEL)[9]. This paper presets a lunar rover architecture that uses many COTS parts, with a focus on electrical parts and their function in and survival of various tests.

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1.2 Google Lunar XPRIZE

The Google Lunar XPRIZE (GLXP) is a privately funded competition to land a rover on the surface of the Moon, travel 500 m and send HD video back to Earth. $30 million USD are available to teams who can complete these requirements, with $20 million USD for the first team to complete the requirements before December 31, 2016.[4]

In October of 2014, XPRIZE announced the Terrestrial Milestone Prize (TMP), a program for teams to be awarded for demonstrating flight-readiness to a panel of independent judges. Hakuto was selected as one of four teams to demonstrate mobility capability. Overall, five teams were selected to demonstrate achievements in mobility, imaging and lander capability. The TMP round concluded in January of 2015, and Hakuto was awarded $500 thousand USD for successfully testing its Moonraker rover with functional testing, thermal-vacuum testing, vibration testing and field testing.[2]

1.3 Hakuto and Space Robotics Lab

Hakuto is the sole entrant from Japan in the GLXP competition and is developing rovers to send as payload on its landing service provider. As of 2015, it is one of 18 teams remaining in the competition. The Space Robotics Lab (SRL) is led by Professor Yoshida in the Department of Aerospace and Mechanical Engineering at Tohoku University in Sendai. It is partnered with Hakuto to design the rovers required for its mission.

1.4 Hakuto Mission and Rovers

In 2009, images from JAXA's KAGUYA (SELENE) spacecraft showed the presence of potential skylights on the surface of the moon[5]. The Lunar Reconnaissance Orbiter (LRO) has also shown several potential skylights. Hakuto's landing service provider has identified one such potential skylights as its landing target. The target is in the Lacus Mortis region at 44.95°N and 25.61°E, south of the Rimae Bürg rille. The skylight is just under 400 m in diameter, with a ramp on one side, possibly formed by a partial collapse. The minimum average slope angle is 13°, although the data from the LRO for this estimation is sparse.[1]

In order to explore a skylight or cave, we developed a dual rover architecture, consisting of a one four-wheeled parent rover (code-named "Moonraker")and one two-wheeled tethered child rover (code-named "Tetris"). In this architecture, both rovers use radio communication via the third-party lander to Earth.

Moonraker will travel near the edge of a skylight with Tetris towed by a tether. The tether, up to 100 m long is wound on a motorized spool within Tetris is used to pull itself back to Moonraker after exploring steep, vertical, or any terrain that the operators wish to "scout" ahead of Moonraker.

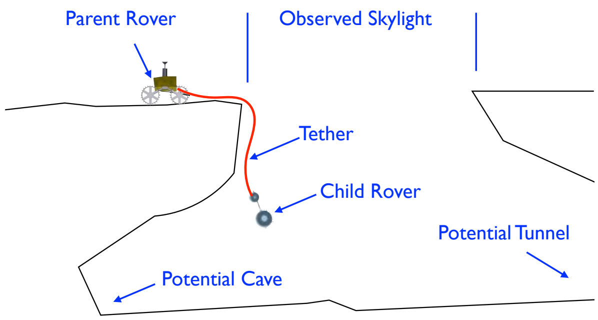


Fig. 1 Hakuto's dual rover mission architecture, with one four-wheeled parent rover and one two-wheeled tethered child rover

Active tethers for similar purpose have been demonstrated by the European Space Agency[6], but they are complex, requiring slip rings and multiple conductors. They would eliminate the need for solar cells or batteries, but we chose a passive tether for two types of redundancy:

Type 1 Operational redundancy: In case of failure of one rover, we can still complete the GLXP requirements.
Type 2 Lander agnosticism: Depending on the lander capabilities, one (Tetris or Moonraker) or both rovers can be integrated, maximizing the number of potential launches

Because both rovers use many of the same or similar components and potentially identical controller architectures, the additional resources required for developing the dual rover system is marginal.

1.4.1 Development Phases

Hakuto has just completed the fourth development phase as described in Table 1. In this phase, within our budget and time constraints, we made the rovers as close as possible to flight configuration. There is overlap in the phases, as environmental and field testing can overlap with the design stage of a subsequent design.

Up until the end of Phase 3, Moonraker was made from an aluminum chassis with nylon body panels, and Tetris was made from an aluminum sheet metal structure. Throughout this time, small iterations to items such as wheel size, grouser length and motor power were made as a result of many field tests and lab experiments.[1] Throughout these phases, the primary goal of the rovers was academic research, with the general requirements of the GLXP used for guidance. Moonraker's development history for the GLXP project goes back to 2009. The addition of Tetris to Phase 2 created Phase 3. We plan to maintain this cycle of "major-minor" updates. Phase 4 was a major update, internally called the "Pre-Flight Model" or PFM. It was de-

Table 1 Description of the phases of development

Phase	Time Period	Description
Phase 1	Jan 2009 to June 2010	Research and Trade Studies
Phase 2 (major)	June 2010 to Sept 2013	Prototype of Moonraker using COTS hardware
Phase 3 (minor)	Sept 2013 to March 2014	Prototype of Tetris added to system
Phase 4 (major)	Jan 2014 to Dec 2014	PFM: CFRP structure, COTS space-ready components and COTS terrestrial components
Phase 5 (minor)	Dec 2014 to Aug 2015	PFM2: Additional/alternate COTS candidate components added
Phase 6 (major)	Jan 2015 to Dec 2016	FM: Final flight configuration
Phase 7	April 2016 to June 2016	FM integration to lander
Launch	July 2016	Tentative Launch date

signed to the flight requirements and every component which was not a space-ready COTS component was designed or selected to qualified to flight-ready status.

A minor update to Phase 4 will also be tested. It will include the flight configuration of all electronics. In parallel, the design of Phase 6 (flight model) will be conducted, with all testing for Phase 5 completed before the Critical Design Review for Phase 6. The overall scheme is illustrated in Figure 2.

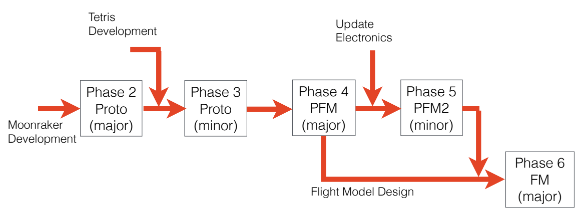


Fig. 2 Hakuto's Major-minor development strategy

2 Phase Four System Architecture

We updated the design for Phase 4 based on the the design and field testing of the Phase 3 rovers. We made minimal changes to overall configuration, but performed extensive detailed design with attention to the thermal and vibration environments expected during the mission.

The criteria for component selection was: mass, power consumption, and use of components with flight heritage, especially by SRL when possible.

2.1 Rovers

The rovers we built for Phase 4 feature an aluminum substructure and Carbon Fibre Reinforced Plastic (CFRP) outer body. We built these in order to meet the requirements for the Terrestrial Milestone Prize detailed in Section 1.2

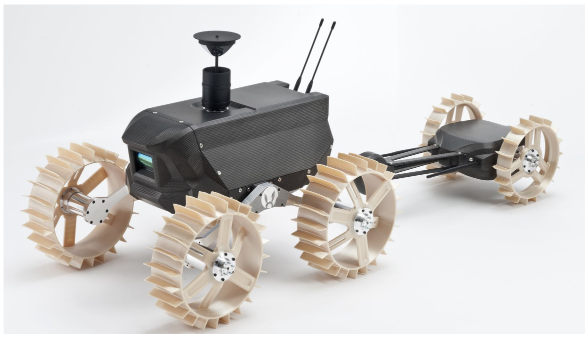


Fig. 3 Phase 4 Moonraker and Tetris rovers

2.1.1 Moonraker

The architecture of Phase 4 Moonraker was based on previous versions. A COTS space-ready FPGA-based controller with a "soft" ARM CPU[7] was selected due to previous experience in integration to COTS parts for the RISING-2 satellite[8]. A COTS cubesat Power Distribution Unit (PDU) and 80 Wh lithium-ion battery, including a watchdog timer, was used for the power subsystem. Solar panels were not included in Phase 4but one solar cell was included on Moonraker to confirm its physical integration and survival of environmental testing.

The omni-directional imaging components, consisting of a COTS USB 5 megapixel camera, lens and parabolic mirror were retained from Phase 3. The camera points upwards to the mirror, to capture a 360 °image that is manipulated by the operator to enable them to look in any direction without the complexity or lag associated with a pan-tilt mechanism.[1] We also kept a COTS laser range-finder from Phase 3 that uses a MEMS mirror to control the pan and tilt of a stationary laser to produce 3D data via a time of flight algorithm.

The main controller is not powerful enough for the real-time HD video processing required by the GLXP, so a COTS ARMv7-based controller was added to handle imaging. This is a readily-available product primarily marketed towards hobbyists, with nearly all signals from the CPU made available on two 48-pin headers making it ideal for a flexible development platform. Other COTS components were picked primarily based on flight heritage and are described in Table 2.

We made two interface boards to connect components. The "power interface" board was used to mount and connect the main controller, ethernet switch, and

PDU. The "imaging interface" was used to connect the imaging controller, camera, radio. Both included minor components such as power relays, ethernet transformers, level converters and multiplexers. Many electrical connections to the interface boards were made by the pin headers factory installed on the PDU and imaging controller. We removed all connectors not designed for aerospace use, such as ethernet and USB, and replaced them with soldered "pigtail" wiring with connectors having space heritage.

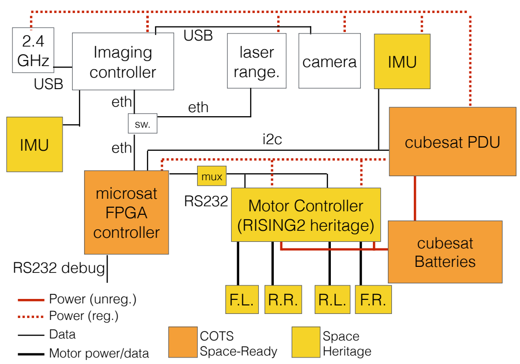


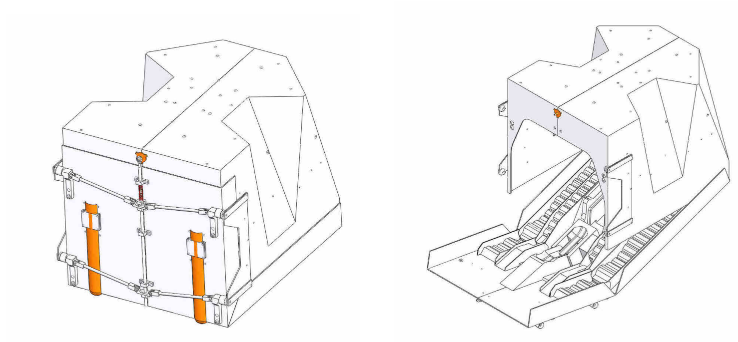
Fig. 4 Moonraker Architecture for Phase Four of Development

2.1.2 Tetris

Tetris' planned architecture for Phase 4 was nearly identical to Moonraker's, with two wheels instead of four, no range-finder, and a tether mechanism added. The total mass of Tetris is 2329 g and the average power consumption budget is 7.3 W.

2.2 Interface to Lander

The lander interface box was made from CFRP and machined parts, with 3D printed Ultem parts in the interior to hold both rovers fixed during the launch, cruise and landing phases. Upon landing, the interface box is opened with a single Shape Memory Alloy (SMA) pin-puller actuator. The open box acts as a ramp with a slope of approximately 30°for easy egress of the rovers on to the lunar surface. Figure 5 shows the interface in the stowed configuration and deployed ramp configuration.



(a) Stowed Configuration (b) Deployed Configuration

Fig. 5 View of the interface box. Moonraker and Tetris are nested inside when stowed. When deployed, the door forms a ramp for the rovers to drive down

2.3 Communication to Ground station

The rovers are configurable with three types of radios: a 900 MHz, 1 W radio supplied by our landing service provider (ethernet interface, TCP/IP and UDP protocols), a 2.4 GHz, 25 mW COTS wi-fi radio (USB interface, TCP/IP and UDP protocols) and a 900 Mhz, 1 W COTS radio (Serial interface).

The supplied radio was not available to us in Phase 4, so the COTS wi-fi radio was used. This allowed us to use the same protocols, in our communication, as in the Flight Models but were limited in range. Due to strict restrictions on radio frequencies and power in Japan, we could not conduct full field testing with Option 3 in Japan. We did perform radio testing in Canada (where the radio is legal to use) to confirm general performance of a 900 MHz radio system at long distances and near obstacles.

3 Testing

In 2014, we thoroughly tested the Phase 4 rovers to determine the suitability of all components for inclusion in the flight model. During these tests, two configurations of the rovers were used:

MTM Model Motors included, but all other electronics replaced by representative masses of approximately the same mass and centre of gravity

Integrated Model All electronics included, except where noted otherwise

A brief summary of each test is included below, followed by the overall results presented in Table 2.

3.1 *Thermal-Vacuum Testing*

3.1.1 Cruise Phase Testing (MTM model)

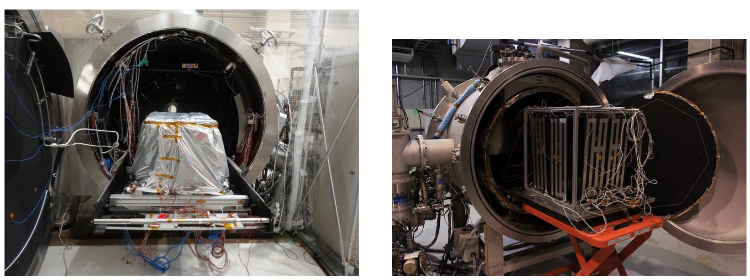
Thermal-Vacuum tests were performed at the Kyushu Institute of Technology established Center for Nanosatellite Testing (CeNT) in the Tobata campus of the Kyushu Institute of Technology. This is a centralized facility with test apparatuses for satellite testing, including thermal-vacuum testing (10^{-5} Pa).

The MTM model of Moonraker, Tetris and the interface box, in the stowed configuration were tested, with sensors at various internal and external points to verify thermal conductance values used in the thermal models.

We simulated the cruising phase of the mission, with the shroud temperature of the vacuum chamber at -173° C, and the interface box wrapped in Multi-Layer Insulation (MLI). The interface box was fastened to an aluminum plate to simulate the deck of the lander. The deck was temperature controlled between 0° C and 40° C.

The data from this test will be used to confirm thermal models and design heaters for the interface box in order to keep the rovers electrical components within their preferred range (with the battery having the most severe requirements of between -20° C and 40° C).

Figure 6 below shows the vacuum chamber used in the test, and the MLI-wrapped interface ready for insertion.



(a) Cruise phase (b) Surface Mission phase

Fig. 6 Experimental setups used for Cruise Phase and Surface Mission

3.1.2 Surface Mission Phase Testing (integrated models)

We performed integrated vacuum testing on Moonraker at Next generation Space system Technology Research Association (NESTRA) at the Kikuicho campus of Waseda University in Tokyo. This is a facility for micro-satellite integration and thermal-vacuum testing. We plan to land 12 hours after sunrise (-166 °C), with deployment at 36 hours after sunrise (-48.2°C) with the GLXP mission complete by

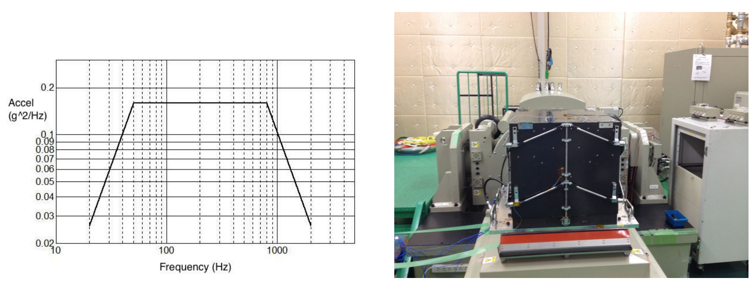
75 hours after sunrise (40°C). The lens and mirror used were COTS products manufactured using the vacuum deposition coatings, so were not tested in oder to avoid contaminating the vacuum chamber through out-gassing.

Figure 6 shows the rover installed on the vacuum chamber testing baseplate. Five panel heaters were placed around the rover. During vacuum conditions, hot and cold tests, to certify operation of the rover up to 75 hours after sunrise were performed. Since our current engineering model batteries do not have battery heaters installed, -20°C was selected for the cold mode temperature. This allows us to validate our thermal model for the system without risk of damage to the batteries (minimum temperature -20°C). 40°C was selected for the hot mode temperature.

The data from this test will be used to confirm thermal models and design radiative cooling for the rovers during the surface mission. Although Tetris was not tested, its similar materials and design mean its thermal model can also be partially validated.

3.2 Vibration Testing

We performed vibration testing to Qualification Level (QT), 14.1 G_{rms}, using motors and representative masses in place of electronics and to Acceptance Level (AT), 10.0 G_{rms}, using fully integrated rovers. These levels come from our landing service provider based on NASA standard GSFC-STD-7000A. The prescribed Power Spectral Density (PSD) is shown in Figure 7 along with the system mounted in the X-axis configuration on a shaker table.



(a) QT Level PSD (b) X-Axis testing

Fig. 7 Vibration testing PSD and experimental setup

3.2.1 QT Level MTM Testing

Although only AT level testing was required for qualification to our landing service provider's requirements, we tested the structures only (by using the MTM models) to QT level of 14.1 G_{rms}. No damage was observed, and the overall modes of vibration were acceptable. However, five structural parts were identified with resonant frequencies near or below 40 Hz. Upon deployment the rovers could freely move down the ramp shown in Figure 5.

3.2.2 AT Level Integrated Testing

We tested the system to AT level of 10.0 G_{rms} with all electronics disabled by holding a normally closed deployment switch open. The integrated testing to AT level also resulted in no damage. Upon deployment, the deployment switch as well as every electrical component functioned correctly, and Moonraker was commanded via a radio link and simulated ground station to leave the interface box. This test was also successful.

3.3 Component Level Radiation Test

We performed component level radiation testing at Takasaki Advanced Radiation Research Institute, Japan Atomic Energy Agency. All electrical components except those with demonstrated flight heritage were tested. Electronic subsystems were placed in front of Cobalt-60 γ source. Precise dosimeters were mounted included to provide accurate measurements of total dose. Exposure time was 4.5 hours, providing a total absorbed dose of 15.3 kilo-rads $\pm 3\%$, about four times the expected total dose (4 kilo-rads). Testing was done with components on, and function tested continuously. All components functioned correctly and without issue except for the imaging controller. This had two reboot events, presumably caused by the effects of radiation. Correct function resumed after reboot. This result was anticipated due to the high density of transistors on the CPU, so our design relies on a watchdog timer on the PDU to reset both controllers if activity stops.

3.4 Field Testing

A field test was conducted at the Nakatajima sand dunes in Hamamatsu Japan. The sand dunes are a lunar analogue site nearly void of all vegetation except some sporadic grasses. Surface features of interest to us are long valleys of soft sand, local hills, steep cliffs, rocky as well as rock-void areas.

All components functioned as expected during the field test, with no major issues. In the presence of a GLXP judge, we successfully traveled 620 m and demonstrated ability to teleoperate in realistic conditions, including a simulated time delay, and a data rate of only 100 kbps.[2]. The only issue uncovered was that the grouser design can pick up rocks which become lodged in the suspension mechanism.

(a) overcoming a 15 cm high rock obstacle during field testing

(b) climbing an approximately 30°slope on soft soil

Fig. 8 Moonraker performance during field testing

3.5 Radio Testing

As described in Section 2.3, the third radio option could not be tested in Japan. We conducted two tests using antenna configurations and heights similar to the flight model in Vancouver, Canada to a distance of 1.5 km, and characterized the performance near obstacles up to 3 m in height so that operators can determine where to expect "dead zones" that should not be traversed.[10]

3.6 Test Results

All of the test results are summarized in the table Table 2. In this table, "NT" is used for items that weren't included in a particular test. Nearly all components passed all tests or has demonstrated flight heritage. The exceptions are shown in the first part of Table 3 with an explanation and proposed resolution.

Each motor uses approximately 10W while the rover is in motion, but in our field testing experience, the rover is stopped much of the time while operators make decisions. Therefore the average power consumption is greatly reduced, to about 12 W.

The main controller for Phase 4 was selected due to its robustness, flight heritage and SRL's experience with it. But HD imaging is a strict requirement of the GLXP competition, effectively making the architecture, as we designed it, dependent on both the imaging and main controllers functioning properly. With this result, for Phase 5 and 6 we merged the function of the two controllers and changed to a redundant computing architecture (Section 4).

As important as the test results was the experience of integration. The wiring shown in Figure 9 is mostly made of a single harness with many connectors. Wiring routing, thermal paths and component placement and connector position can all be greatly improved to reduce integration time and decrease wiring mass.

Table 2 Summary of test results for Moonraker

Component	Description	Thermal	Vibration	Radiation	Field	Flight Heritage	Mass (g)	Power (W)
Wheels	3D Printed Ultem	Pass	Pass	NT	Fail	No	1980	0
Structure	Machined aluminum	Pass	Marginal	NT	Pass	No	1246	0
Mechanical Parts	Machined aluminum	Pass	Pass	NT	Pass	No	1793	0
Fasteners	Steel	Pass	Pass	NT	Pass	No	125	0
Body	CFRP	Pass	Marginal	NT	Pass	No	725	0
Motors	12W brushless	Pass	Pass	NT	Pass	RISING-2	696	12
Motor Controller	Custom SH2A-based	Pass	Pass	NT	Pass	RISING-2	32	1
Camera	5MP USB camera	Pass	Pass	Pass	Pass	No	10	1
Lens	COTS C-mount	NT	Pass	NT	Pass	No	105	0
Mirror	Hyperbolic mirror	NT	Pass	NT	Pass	No	78	0
Range-finder	MEMS-based laser	Pass	Pass	Pass	Pass	No	480	6
Imaging Controller	ARMv7 COTS (hobbyist)	Pass	Pass	Pass	Pass	No	40	0.5
Batteries	80Wh, 15V COTS (cubesat)	Pass	Pass	NT	Pass	cubesat	473	0.1
Power Unit	COTS (cubesat)	Pass	Pass	NT	Pass	cubesat	105	0.5
Solar Cells	1 Triple Junction cell	Pass	Pass	NT	Pass	Yes	3	0
Wiring	COTS (MIL spec, industrial)	Pass	Pass	Pass	Pass	Yes	220	0.3
Radio*	See note	Pass	Pass	Pass	Pass	No	18	1
Main Controller	COTS (space-ready)	Pass	Pass	NT	Pass	No	15	1.5
Deployment Switches	COTS	Pass	Pass	NT	Pass	No	20	0
Debug/charge interface	COTS (MIL spec)	Pass	Pass	NT	Pass	No	30	0
Power Interface board	SRL made	Pass	Pass	NT	Pass	No	35	0.1
Imaging interface board	SRL made	Pass	Pass	Pass	Pass	No	55	0.1
Mass memory	controller on-board eMMC	Pass	Pass	Pass	Pass	No	0	0
IMU	COTS	Pass	Pass	Pass	Pass	cubesat	10	0.1
Ethernet Switch	COTS (UAV)	Pass	Pass	Pass	Pass	No	35	0
Power Switches	COTS	Pass	Pass	NT	Pass	No	50	0
Charging board	SRL made	Pass	Pass	NT	Pass	No	45	0
Totals							8424 g	24.2 W

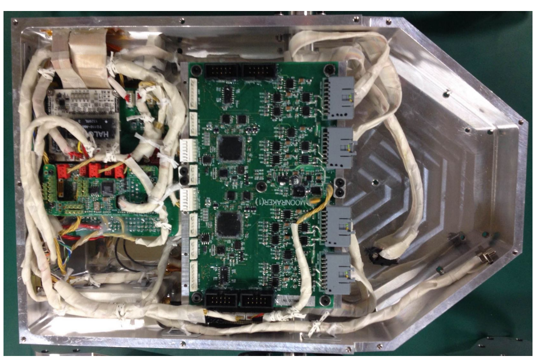


Fig. 9 Moonraker's internal components, with complex wiring harness.

4 Phase Five Architecture

We are now using the results of Phase 4 development to design and fabricate the Phase 6 rovers. Aside from the change in controller, only minor changes are specified by the test results themselves, as described in Table 2. All updates to electrical components, wiring and connectors will be tested in the Phase 5 rovers before the Critical Design Review for Phase 6.

4.1 Changes from Phase Four to Phase Five and Six

At the time the lander interface was not fixed, so the interface boards and wiring harness included options for different interconnections and protocols. This was flexible for development but now these options have been reduced so there are mass savings and opportunities for the FM. Many connectors can be removed and/or consolidated. To simplify wiring, all signal routing will take place on the interface boards. “Straight” cables with identical pin assignments on both sides are also easier to specify and purchase as items from suppliers with quality-control certifications.

HD video is a strong requirement that demands a capable controller, redundancy for both the main controller and imaging controller (and camera) is a hard requirement. Since the imaging controller is capable of the main controller functions, and passed all environental testing in Phase 4, we made a new architecture with identical controllers, each connected to a cameras. This way, redundancy is created, development time is reduced (because a heterogeneous architecture does not have to be supported).

Phase Four used a USB camera but the flight model will change to use the same imaging sensor’s native parallel interface. This will eliminate the camera’s on-board USB circuitry and approximately 500 mW of power consumption. Wwe chose a 10 g, “System on Module” (SOM) board with only the components that we require. Most available SOMs include unnecessary components such as DC-DC converters and HDMI ports, or do not route all of the required interfaces to the CPU. The Phase 4 controller was approximately 40 g and included many components that use power and add failure points. Debug and charge interfaces will also be made modular so they can be removed prior to flight to save mass.

The testing regimen for this phase will be similar: radiation testing, thermal-vacuum testing, vibration testing and field testing. Although architecture changes have been minimized, the change of controller described above presents a large risk, if it is not qualified before the rest of the electronics systems are designed and manufactured. This is because, due to time constraints and subsystem interdependencies, it will be difficult or impossible to change the controller. Therefore the first step of Phase 5 is fabrication of prototype boards so that component-level radiation testing can be completed ahead of detailed design.

The design target for the flight model Moonraker is a reduction of mass from 8.4 kg to 4.0 kg and of power from 24 W to 18W. Approximately half of the re-

Table 3 Phase Six changes for Moonraker

Component	Issue	Solution
Wheels	Rocks can get stuck in grouser	Modify grouser for clearance of suspension
Main controller	Some parts near 40 Hz threshold	Stiffen parts for FM design
Structure and Body	Integrated structure will save mass	Remove aluminum substructure
Thermal interfaces	Integrated structure will save mass	Remove thermal paths, integrate design to structure
Deployment Switches	Not radiation tested	Passive components; testing not required
Debug/charge interface	Not radiation tested	For development; not required for FM
Power Interface board	Not radiation tested	Iterate design and radiation test
Power Switches	Not radiation tested	Not required for FM
Charging board	Not radiation tested	For development; not required for FM
Main interface board	New controller architecture	Change from COTS ARM-based board to custom
Wiring	New wiring standard for FM	Change connectors to MDM
Camera	Redundant architecture for FM	Change to parallel interface, add camera
Range-Finder	Reduce power consumption and mass	Change from laser-based to camera-based
Debug interface	Not needed for flight configuration	Make removable debug interface
Switch interface	Not needed for flight configuration	Remove from design
Charge interface	Not needed, use solar interface	Use external connector for solar cell simulation

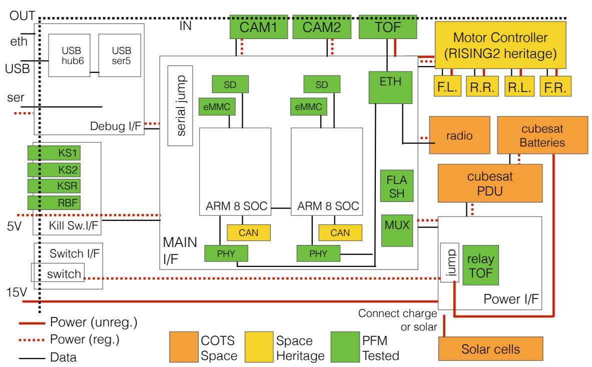


Fig. 10 Moonraker Flight Model architecture

duction in mass will be achieved by removing the aluminum substructure. The rest is achieved by small reductions in each subsystem. Reduction in power is achieved by replacing the laser rangefinder changing away from a heterogeneous controller architecture, as well as removing unnecessary interfaces (such as USB).

5 Conclusion

Through extensive radiation testing, vibration testing, thermal-vacuum testing and field testing, we have demonstrated a dual rover architecture using many space-ready and terrestrial COTS components. This architecture is capable of completing both the GLXP mission requirements and exploration of a potential lava tube skylight on the surface of the moon. We have identified five structural parts to be redesigned, and changed from a heterogeneous controller architecture using both a space-ready main controller and ARM-based imaging controller to a dual, COTS, ARM-based architecture. This has allowed us to reduce mass, number of components, power consumption and development time even while adding a redundant camera and theoretically increasing reliability of the overall system. The use of COTS components has allowed us to start from a convenient, inexpensive flexible architecture for development and arrive at purpose-built, power-efficient architecture by removing components and options for interconnections over time. The overall development strategy of alternating large overall design changes and small subsystem iterations was also effective.

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