FLIGHT SYSTEM ARCHITECTURE OF THE SORATO LUNAR ROVER

*John Walker[1]

[1]ispace, 3-1-6 Azabudai, Minato-ku, Tokyo, Japan, E-mail: j-walker@ispace-inc.com

ABSTRACT

ispace, a Japan-based private lunar exploration company has developed lunar rovers over the course of several iterations, originally for its Google Lunar XPRIZE mission called "Team Hakuto". A flight model rover called "Sorato" was developed and qualified for the mission.

Sorato is a 4-wheel, skid steer rover with passive suspension and a minimum of actuators. The rover has two redundant controllers, inertial measurement units, four cameras, and one time-of-flight camera for detecting obstacles and making 3D images. The rover also carries a deployable antenna and has payload capacity.

Sorato is smaller than any lunar or martian rover, at 3.8 kilograms. This mass was achieved by reducing the power consumption as much as possible, thereby reducing the surface area required for both radiators and solar cells, minimizing mass and by a novel thermal design.

The rover makes use of magnesium alloy, carbon fibre structure and low-thermal conductivity plastics, to thermally isolate the solar panels and lunar surface from the electronics. The top of the rover is concave which acts as a heater in the lunar morning and a radiator at lunar noontime.

Many parts in Sorato are Commercial-Off-The-Shelf (COTS), qualified through extensive screening, especially radiation screening. The entire system was designed, manufactured, and qualified at the system level. COTS components allow rapid development and higher performance compared to traditional space products.

1 INTRODUCTION

ispace is a lunar exploration company based in Tokyo, Japan. It intends to travel to the lunar surface, find and utilize resources, particularly water-ice which is thought to exist at the lunar polar regions. ispace plans to do this in a cost-effective and profitable way through its expertise in miniaturization of spacecraft and lunar rovers, beyond the lower bounds established by space agencies.

ispace created a four-wheeled lunar rover called Sorato as part of its entry into the Google Lunar XPRIZE (GLXP) as "Team Hakuto." Although GLXP and Team Hakuto have ended without a winner and without a lunar mission, Sorato is the baseline rover technology for ispace.

This paper presents the final architecture of the 3.8kg Sorato rover, results of qualification and briefly shows the conceptual design of the next ispace rover, carried to the lunar surface by its own lunar landers. ispace's first orbiter mission is planned for 2019/2020 and the first landing/roving mission is planned for 2020/2021.

2 HISTORY

The conceptual design and prototyping for a GLXP rover stretches back to 2010 at the Space Robotics Lab (SRL) of Tohoku University[1] as shown in *Figure 1.*

Figure 1: The "Moonraker" 10kg four-wheel prototype rover, with the "Tetris" two-wheel rover (inset)

ispace has since developed both two- and four-wheel rovers, for independent operation as well as for cooperative operation to explore a lunar skylight. The rovers are described in *Table 1*. The power consumptions shown are for 10% "duty cycle" driving unless otherwise stated. That is, 10% of time is spent driving, and 90% of time making decisions. This number is chosen based on ispace's field test experience for operation at sub-100kbps bandwidth.

All rovers include ispace's qualified motor controllers and Inertial Measurement Units (IMUs). All of the four-wheel rovers use the same basic principle of 4-wheel skid steering, with a simple passive differential gear system to keep all four wheels on the ground.

Table 1: History of ispace rovers since 2013.

Name	Description
"Pre-Flight Model" (PFM)	*Description*: 4-wheel rover *Camera*: 5MP omni-directional camera + mirror *Radio*: 900 Mhz proprietary + 2.4 Ghz wi-fi (1 antenna for each) *Controller*: FPGA space-ready main controller + ARM imaging controller *Mobility*: 4 in-wheel motor *Solar Power*: none *Battery*: space ready Li-ion, 77Wh *Mass*: 7.0kg *Power*: 18W *Description*: 2-wheel rover (tethered) *Camera*: 5MP *Radio*: 900 Mhz proprietary + 2.4 Ghz wi-fi (1 antenna for each) *Controller*: ARM controller *Mobility*: 2 in-wheel motor *Solar Power*: none *Battery*: space ready Li-ion, 38Wh *Mass*: 1.5kg *Power*: 10W
"Pre-Flight Model 2" (PFM2)	*Description*: 4-wheel rover *Camera*: 4x 5MP *Radio*: 900 Mhz proprietary + 2.4 Ghz wi-fi (1 antenna for each) *Controller*: 2x ARM controller (redundant) *Mobility*: 4 in-wheel motor *Solar Power*: None *Battery*: space ready Li-ion, 77Wh *Mass*: 7.0kg *Power*: 15W
"Sorato Flight Model 1" (FM1)	*Description*: 4-wheel rover *Camera*: 4x 5MP *Radio*: 2.4 Ghz proprietary *Controller*: 2x ARM controller (redundant) *Mobility*: 4 in-wheel motor *Solar Power*: 18W @ 45N *Battery*: space ready Li-ion, 77Wh *Mass*: 5.0kg *Power*: 13W
"Sorato Flight Model 2" (FM2)	*Description*: 4-wheel rover *Camera*: 4x 5MP *Radio*: 2.4 Ghz proprietary *Controller*: 2x ARM controller (redundant) *Mobility*: 4 in-wheel motor *Solar Power*: 11 W @ 28N *Battery*: space ready Li-ion, 38Wh *Mass*: 3.8kg *Power*: 13W (at 20% duty cycle)

Figure 2: The "PFM" two- and four-wheel rovers

Since the PFM rover, all components have been qualified through radiation (total dose, single event), thermal vacuum and vibration testing, and system environmental testing. Progress was made by reducing the power consumption with each iteration, thereby decreasing required power, solar panel size, and total rover mass. In each phase, screening and qualification testing was performed.

Figure 3: The "FM1" Sorato four-wheel rover

In PFM, the omni-directional camera system was usable but its height required a tall support structure to support the rover during launch, which added significant mass. It was replaced by 4 cameras with overlapping fields of view in PFM2. PFM had a heterogeneous architecture, with a high-reliability FPGA-based controller plus a COTS ARM controller to meet the imaging requirements. The ARM controllers passed radiation screening so PFM2 was updated to a redundant ARM controller architecture. This general concept was kept until FM2.

The FM1 rover was designed for the thermal environment at 45N and was qualified at the component and system level[2], especially by mobility, thermal vacuum, and vibration testing. Testing was used to validate analysis models used for FM1, and allow three major, related changes to be made for the FM2 rover: power reduction, thermal design, and mass reduction.

Partway through the FM2 design, the landing partner was changed and the landing site was changed from 45N to 28N. This hotter location required improved thermal design by less heating and more cooling. Less heating was accomplished by lower power consumption, primarily by using more efficient motors. Less power consumption allowed smaller solar panels and batteries. Smaller solar panels allowed a shorter rover. More efficient motors, smaller batteries, and a shorter rover all contributed to a lower mass, along with change to a monocoque structure.

3 SORATO FM2 ROVER

3.1 Requirements

The requirements for the rover came from four main inputs: 1) The expertise and business planning of SRL and ispace, 2) The GLXP requirements, 3) The specific environmental requirements of the mission and landing site and 4) Constraints of the landing partner. The landing site at 28N was selected by the landing partner as a relatively safe site with few rocky outcrops and with relatively good available terrain data. *Table 2* gives a summary of the requirements. All of these were met through design or testing.

Table 2: Top level requirements for Sorato

Source	Category	Requirement
GLXP	Imaging	NRT Video
		HD Video
		High res panorama
	PR	GLXP logo shown
		Looks cool
	Mobility	Travel 500m total
		Travel 250m from lander
ispace	Mobility	22 degree slope climb
		Overcome 10cm rocks
		Autonomous stop
		0.1m/s speed
	Budget	Mass < 4kg
	PR	Sponsor logos
	Power	10% driving time
Landing site	Thermal	Surface temperature to 100C
	Power	Sun angle to 28 degree
	Radiation	Up to 80MeV
Landing Partner	Radiation	Up to 4krad total dose
	Structure	> 60 Hz eigenfrequency
		20G quasi-static
	Mission time	(proprietary)
	Thermal	Isolate from lander
	Comm	2.4 Ghz, 1W radio
		125 bps uplink (33% of time)
		118kbps downlink (50% of time)
		CCSDS, Proprietary ground station

The GLXP imaging requirements are detailed but essentially require a narrow field of view, with 1-2fps "Near-Realtime" (NRT) 640x480 video for operation and 10fps 1280x720p HD video sent to Earth (non-realtime)[3]. Based on the above requirements, the mobility, thermal, and structure detailed designs were created.

3.2 System

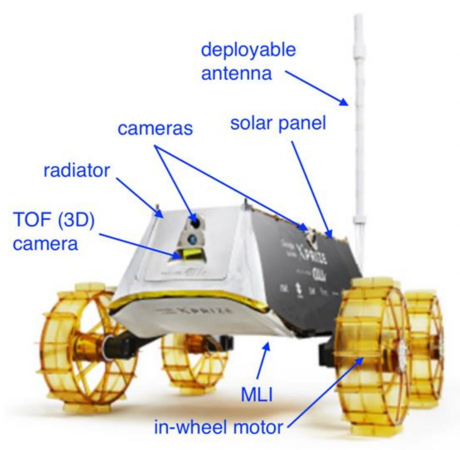

Figure 4: Sorato Rover, antenna deployed

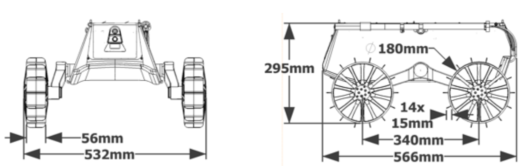

Figure 5: Dimensions of Sorato, antenna stowed

Total mass of the rover is 3.8kg (without the "interface" to the lander structure. The maximum speed is approximately 0.1m/s and the power consumption is 4.5W at idle (including communication) and an average of 21.5W while moving across varied terrain.

The rover is designed to be dropped from the deck of the lander to the lunar surface. The component which holds and drops the rover is called the interface, shown below. It has 3 main functions: deployment using a COTS actuator, thermal isolation of the lander to the rover, electrical interface for heaters inside the rover (used during cruise).

3.3 System Architecture

Aside from connecting the subsystems, the defining feature of the architecture is the two redundant ARM controllers located on one ispace-designed board.

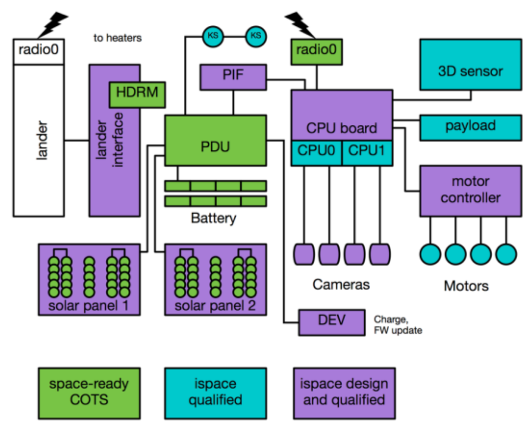

Figure 6: Sorato Rover Architecture

3.4 Mobility

The four-wheel skid steer concept was kept as it has been successful for ispace. The mobility system comprises an ispace motor controller, 4 COTS (but customized) brushless DC gearmotors inside each of four wheels, and ground clearance and wheel size maximized for the available space on the lander. The wheels are mass-optimized based on previous research at SRL which concludes approximately 15 grousers with 15mm length is an optimum point for travel efficiency vs performance[4]. The mobility system can generally traverse over 10 cm obstacles or higher and remain stable at slopes approaching 30 degrees.

3.5 Thermal Design

The interface is designed to thermally isolate the rover from the lander. This is accomplished by MLI placed inside and outside the interface and ensuring the contact points of the rover near the lander are as small as possible. During cruise, the lander provides power to several heaters inside the rover, particularly near the battery.

During the surface phase of the mission, the surface of the moon ranges from about -40 to 100C at lunar noontime. Therefore, the bottom of the rover is insulated by MLI (inside and outside of the monocoque). The bottom and sides of the rover become hot due to the solar panels, therefore all electronics are mounted on top of the rover, directly to magnesium radiators with a silver-teflon thermal control surface. The top of the rover is essentially magnesium, and is thermally isolated from the rest of the rover by Ultem plastic. The wheels are made from the same plastic, to thermally isolate the rover from the surface. The top of the rover can maintain a temperature 50C lower than the bottom of the rover.

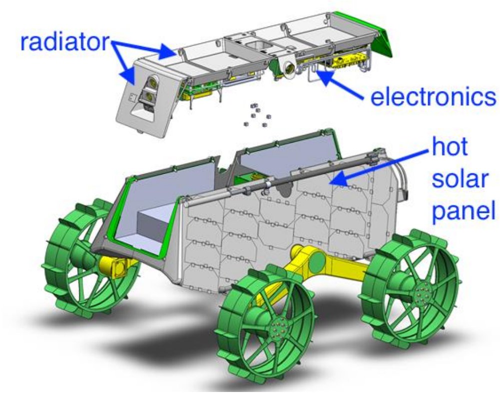

Figure 7: Electronics are located on the top of the rover

The top of the rover has a concave shape comprising near-vertical sections with high absorptivity and horizontal sections with low absorptivity and high emissivity. By this design, the top of the rover acts partially as a heater when it has a high view-factor to the sun while it is low in the sky, and acts primarily as a radiator when the sun angle is higher.

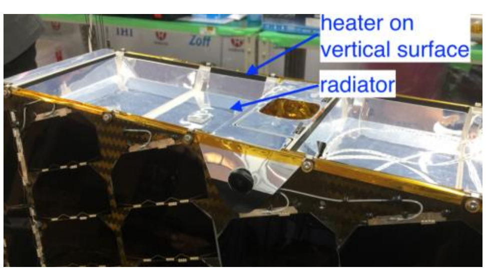

Figure 8: Detail of the heater function of the radiator

3.6 Structure

Aside from the thermal design, the interface is designed to make the rover as stiff as possible when connected to the lander. To do this, there are 12 points which constrain the rover, plus one actuation point in the middle of the rover. The interface is constructed from CFRP with Nomex honeycomb, and is approximately 20mm thick in total.

The rover is constructed mainly from CFRP with Nomex honeycomb, and is approximately 3.5mm thick. Note that the requirements for the vibration environment are largely met by the interface, while the rover mass is minimized. Other components are generally machined from low density, high thermal conductivity magnesium or titanium where strength was required.

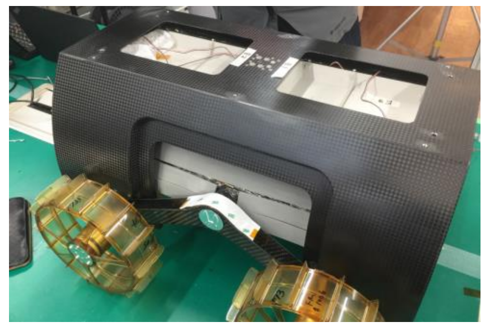
Figure 9: Sorato inside the interface, shown without MLI for clarity

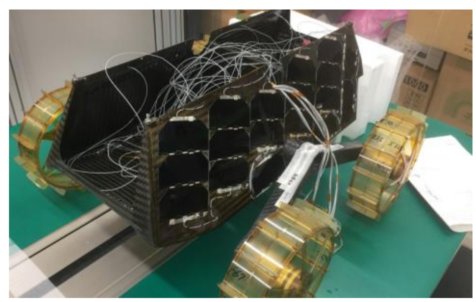
Figure 10: Sorato "bottom" showing monocoque construction, mid-integration

3.7 Imaging

Four cameras are connected by the cameras' native interfaces to the Image Processing Unit (IPU) of the controllers. This is key to reduction in power consumption and is based on smartphone architecture. A conventional robotics camera has a local controller. By using a "native" interface connected to the IPUs, the local controller and most of the data handling is avoided, saving power. The IPU obtains frames from the camera and hardware compresses them as the first step. Raw frames do not need to be handled by the CPU. Unlike typical space applications, Sorato uses H.264 movie compression, not still images

A Time of Flight (TOF) camera is also included on the front of the rover. It is required to detect obstacles which may be undetected by the operator and may be dangerous for the rover to traverse (i.e. less than the 10cm height the mobility system can easily handle). The TOF camera is a COTS design customized for ispace with a laser light source more suited to the lunar lighting environment. It functions to 2-3m and can create a point cloud for the operator to download and/or generate a local map of obstacles and perform emergency stopping function. The overlapping combination of this function plus mobility over obstacles is key to rover success.

3.8 Communication

The communication system was heavily constrained to the landing partner's lander design and ground station design. The most difficult constraints include a maximum downlink speed of 118kbps, time multiplexed to 50% at the sub-second level and a maximum uplink speed of 125bps, time multiplexed to 33% at the second level.

The proprietary 2.4 Ghz radio was made from COTS components, but required extensive testing and design updates to reach the required performance. The specific details of packetization for a CCSDS compliant system and time multiplexing are beyond the scope of this summary report.

Meeting the distance requirements of GLXP with margin and varied terrain was done by selecting an optimum antenna and placing it as high as practicable on top of the rover. The top of the antenna is 700mm from the ground. This is achieved by developing a titanium spring mechanism and using a COTS actuator to deploy it on the lunar surface.

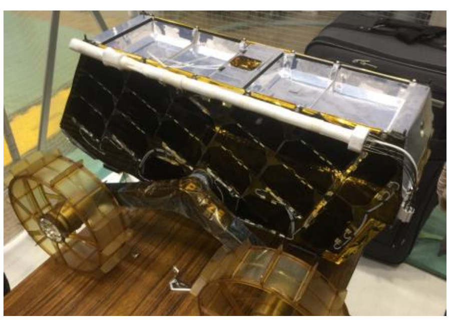

Figure 10: Sorato, antenna stowed

3.9 Operation

The rover is designed to be operated primarily by one pilot and one co-pilot. Additionally, one mission manager handles mission planning and one or two system or support engineers are available to support mission planning based on operational constraints, temperatures, power requirements, etc. The screens offer an interface to send commands for driving, check all telemetry and alarm conditions, receive images, video, obstacle detection information and download additional data such as point clouds when required for additional analysis. Obstacles detected by the TOF are both displayed on an overhead 2D map, and overlaid on the camera images.

Figure 11: Sorato pilot screen (1 of 2 screens)

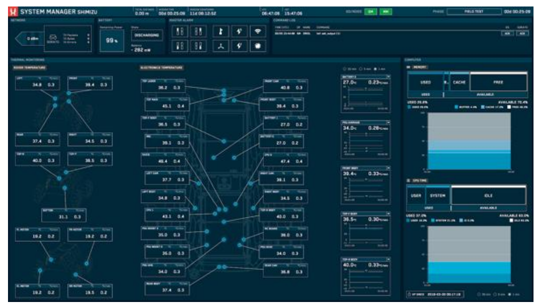

Figure 12: Sorato co-pilot screen (1 of 2 screens)

Telecommands are uploaded via a ground station network and lander and telemetry/images are downloaded via the lander and a ground station network. The detailed communication architecture is out of the scope of this report.

4 COMPONENT SCREENING

The specific components for Sorato were chosen based on past experience (updated from older rovers), primarily as COTS at the small component level (for example, CPU, memory, and camera sensor). The PCBs for all subsystems were designed by ispace and manufactured in Japan with the exception of the power distribution unit, which was procured from a cubesat supplier.

The following types of component level qualification was carried out: 1) Vibration testing to 25Grms, 2) Thermal vacuum test for maximum and minimum expected temperatures, 3) Thermal cycle test (150 times, -40-80C), 4) X-ray inspection (for COTS PCBs with ball-grid array components), 5) Single event effect (to 80MeV), 6) Total Ionizing Dose test (to 20 krad).

This testing was done many times, when a candidate for a component was selected and when the designed was finalized. Historically, approximately 70% of selected components passed screening. Over time, the following For the Sorato FM2, 100% of selected components and 100% of final designs passed.

5 SYSTEM QUALIFICATION

The qualification strategy was based on producing 3 rovers: 1) Flight item, 2) Flight spare: identical to above, 3) Field test rover: Nearly identical to the above, but some added components for field testing including RTK-GPS, debug connectors and an additional battery to simulate solar charging on Earth. Solar cells and thermal gear was not installed.

6.1 Environmental Testing

System level environmental testing of Sorato was performed. The test levels for the mission are proprietary, but the following levels were used for thermal vacuum and vibration testing at the system level:

Table 3: Vibration testing levels for Sorato

Name	Description
LL	Low level (0.5G or 0.5 Grms), for evaluating eigenfrequency response before and after higher level tests
MSL	Minimum Specification Level, for verifying that a configuration change does not have a workmanship issue
AT	Acceptance Test level, approximately the expected level in flight.
PFT	Proto-flight level, above the expected level in flight

Each vibration testing level includes a specification for random vibration testing and sine-sweep vibration testing and differing levels for each of 3 axes. The full vibration tested program was designed with the launch provider to test to the local environment of the rover in the lander system, the 20G quasi-static requirement, and to verify the eigenfrequencies against the predicted values and requirement.

The protoflight level was used rather than a “Qualification Test” or “QT” level used on some programs. Protoflight level is somewhat higher than AT, but lower than QT. This gives confidence to all stakeholders that one spacecraft was tested beyond the predicted levels (there is safety margin) but has a lower level of risk to reduce the spacecraft lifespan or reliability. This is important for a minimum mass design and important for a “newspace” project to reduce the number of spacecraft required. Minimum eigenfrequency of 58 Hz was determined.

Thermal-vacuum testing was performed with the interface and simulated lander for the “coldest case”, which is during cruise. It was performed with the rover and simulated lunar surface for the “hottest case” of lunar noontime. Predicted temperatures were within 10C, and all rover functions worked before, during and after testing, verifying the design. Thermal-vacuum testing was also used to calibrate the thermal analysis models and predict results at other times of day, rover orientation, etc. The updated models confirmed confidence in the design for the mission.

Table 4: Thermal-Vacuum test levels for Sorato

Name	Description
Cold case	With rover inside lander interface and simulated lander. Chamber Shroud kept at minimum temperature, “Lander” kept at -40C and heaters enabled
Hot case	With rover and simulated lunar surface. Surface kept at 100C and IR lamps used to simulate maximum solar cell input and solar flux input to rover structure and radiators

The following image summarizes the environmental testing program.

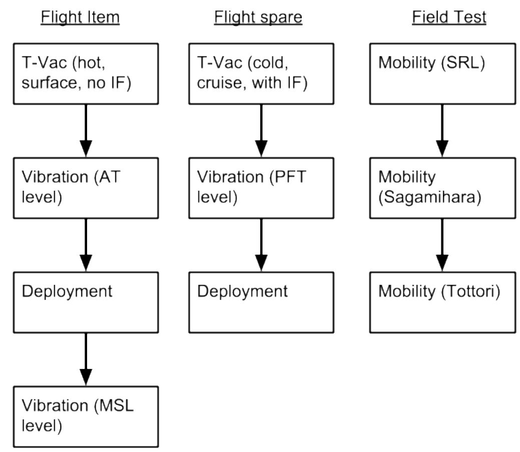

Image 13: Test Philosophy of the 3 rovers

Both the flight item and flight spare were testing in a sequence of thermal vacuum and vibration to simulate the launch sequence. After successful deployment testing, the flight item was re-assembled and vibration tested to MSL to ensure no change in stiffness, and then shipped for integration with the lander. All vibration testing was successful, with no damage indicated and all rover functions working before and after testing. Deployment was also successful.

6 FIELD TESTING

Field testing is useful for evaluating mission planning, user interfaces, operator training. It is partially done in a quantitative way (for example formally checking all rover functions within the entire system), and partially done in a qualitative way.

6.1 Quantitative Field Testing

Field testing, defined as physical system level testing in an analogue environment was performed in 3 locations: the SRL facility’s sandbox, the indoor field test facility at JAXA’s facility in Sagamihara, Japan, and a natural sand dune site at Tottori, Japan. *Table 4* gives a summary (at subsystem and general topic level of the quantitative field testing results):

Table 4: Quantitative field testing results

Location	Test	Result
SRL	Slope to 22deg	Pass (stable)
	Max slope	25deg (slip ratio=0.6)
Saga-mihara	Imaging to specification	Pass
	10cm obstacle	Pass
	Characterize obstacle performance	Identify dangerous rock sizes
	TOF obstacle detect	>5cm
Tottori	Operation at 250m	Pass
	500m operation	Pass
	All telecommand	Pass
	All telemetry	Pass
	Imaging for mission planning	Pass
	TOF obstacle detect during operation	Pass

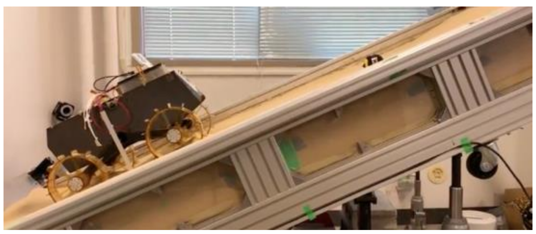

Figure 14: Maximum slope testing at SRL

6.2 Qualitative Field Testing

During field testing, several other findings were made. Most importantly, the image quality, and especially NRT quality which met specific requirements, was better than expected. Only 48kbps are available for NRT, but the images obtained at 1-2fps were good enough for operators to run the rover for 20% of the time (double the design duty cycle). 1-2 cm variations in terrain and obstacles could be discerned.

Figure 15: Frame obtained by the NRT video system at 2fps, clearly showing terrain

Usability testing was performed while operation of the rover was underway with untrained operators, who could successfully determine the operating procedures and constraints within several minutes.

Figure 16: Usability testing during field testing at Tottori, Japan, showing all 4 screens

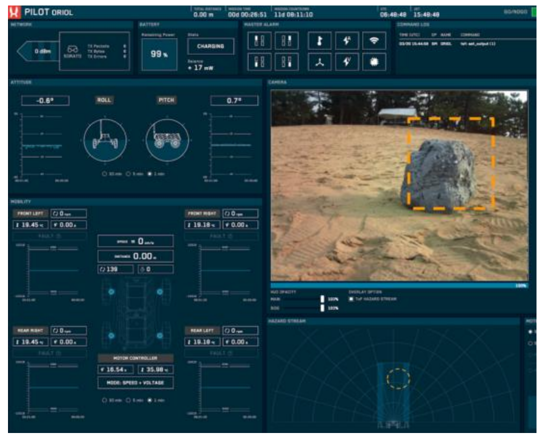

Figure 17: UI showing obstacle detection overlay on image and position on 2D map

7 CONCLUSION

All requirements indicated in *Table 2* were met, as shown in *Table 5*. Green items were qualified by design and approval, and blue items were qualified by design and testing.

Table 5: Top level requirements for Sorato

Source	Category	Requirement
GLXP	Imaging	NRT Video
		HD Video
		High res panorama
	PR	GLXP logo shown
		Looks cool
	Mobility	Travel 500m total
		Travel 250m from lander
ispace	Mobility	22deg slope climb
		Overcome 10cm rocks
		Autonomous stop
		0.1m/s speed
	Budget	Mass < 4kg
	PR	Sponsor logos
	Power	10% driving time (20% achieved)
Landing site	Thermal	Surface temperature to 100C
	Power	Sun angle to 2deg
	Radiation	Up to 80MeV
Landing Partner	Radiation	Up to 4krad total dose
	Structure	> 60 Hz eigenfrequency*
		20G quasi-static
	Mission time	(proprietary)
	Thermal	Isolate from lander
	Comm	2.4 Ghz, 1W radio
		125 bps uplink (33% of

		time)
		118kbps downlink (50% of time)
		CCSDS, Proprietary ground station

* 58 Hz was achieved, which was deemed acceptable by negotiation with the landing partner.

The result of development of an easy-to-use UI and good results of image quality allowed operation at 20% duty cycle, as opposed to the 10% requirement.

7.1 Lessons Learned

The Sorato program was successful, largely due to the opportunity to develop several iterations and improve in a step-by-step manner, as shown by qualification results. Outside of those results, there were "lessons learned" about COTS. 1) COTS components should be on the shelf. COTS electronics components have many advantages over traditional space components, but they require additional qualification, and often are discontinued or go out of stock. To use COTS components, one must be prepared to both update and re-qualify subsystems as technology progresses, and stock significant quantities to account for future programs and development. 2) One of the best advantages of COTS components is accessible software support. This should be one of the major selection criteria.

7.2 Future ispace Missions and Rovers

The ispace business plan calls for a lunar orbiter mission in 2019-2010 and a lunar lander/rover mission in 2010-2011 followed by travel to the lunar surface once per month. This requires much better standardization of rover technologies and the ability to integrate payloads for customers quickly. As ispace plans to travel to polar regions to find and utilize resources (especially water), the first several missions are designed to build up the requisite technology for mobility and cold temperature roving. Therefore, the following requirements will be considered for the next rover: mobility in dangerous or vertical terrain (using the tethered system), standardization of mechanical, electrical, and data payload interfaces and operation in radio and sunlight denied areas. Over the course of several missions, extreme temperature, resource sensing and resource utilization will be added.

References

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