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ROVER ORIENTATION ESTIMATION USING SUN SENSORS FOR LUNAR AND PLANETARY EXPLORATION

Takuto Oikawa
Tohoku University, Japan, oikawa@astro.mech.tohoku.ac.jp

Jasmin Bröhan
Hamburg University of Technology, Germany, jasmin.broehan@tuhh.de

Gabriel Dubernet
Ecole Nationale Superieure des Sciences Appliquees et de Technologie de Lannion (ENSSAT), France, dubernet.g.e@gmail.com

Kazuya Yoshida
Tohoku University, Japan, yoshida@astro.mech.tohoku.ac.jp

For space exploration rovers, knowing the exact local orientation is difficult due to the absence of Global Position System. From the global information (landing site) and the rovers images, the operator can make a rough estimation of its current position. Although this approach requires an active operator at all time, it is a very simple way of obtaining a position estimation. While the rover is in motion, wheel slippage is considered as it can be a source of heading error and diverge away from the intended motion plan. This problem is approached by tuning the wheel rotation speed based on the slip condition from terrestrial testing by mimicking the target environment. This method would be sufficient if the rover is landing at a pre-explored region such as the Apollo mission site. However, the above practice does not work when the rover travels to a previously unexplored area as the tuning parameters will not necessarily be optimal. Therefore, we need a robust system that can track the rovers absolute orientation regardless of terrain conditions.

In this paper, we will present an approach using commercial off-the-shelf photodiodes as sun sensors. Arrays of diodes are added onto the rover; each installed on a different surface to measure all necessary directions. The calibration process is initially performed in a controlled environment with a single artificial sunlight emitter to measure the sensors functionality. The test results are then compared with the outdoor condition to measure errors such as environmental noise from surface albedo. As a final validation process, a field test is conducted to show the rovers local orientation based on the sun heading. The rovers yaw estimation is during spot turn operations, and the deviation is compared to the angle derived from the ground truth. Finally, we will determine the solar elevation angle based on the sensor information and compare with the global solar orientation.

I. Introduction

I.i Sensor Designs

Compared to other approaches like using a linear photodiode array under a slit by,[?] a much simpler method will be applied by installing commercial off-the-shelf photodiodes as sun sensors on five different rover surfaces. Therefore the sun incident angle on the front, left, right, back and top side of the rover will be measured, since the photodiodes are angle sensitive. By comparing the voltage outputs on each surface, the azimuth and elevation angle of the sun can be calculated. The sensors will be mounted with a 3D printed interface to ensure a perpendicular photodiode heading direction on the surface.

II. History of ispace and Hakuto

From a starting field of 30 in the GLXP competition, Hakuto is one of five teams to win exclusive Terrestrial Milestone Prizes in January 2015, one of five to remain in the competition since a January 2017 deadline to obtain a launch contract, and one of just a few remaining. by Hakuto is operated by ispace Technologies, Inc, a Tokyo-based aerospace startup. It is partnered with several companies and the Space Robotics Lab (SRL) of Tohoku University. SRL's history of rovers and satellite missions are the basis for ispace's technologies and SRL conducts research to support future space missions.

II.i "Sorato" Four-wheeled rover

The primary rover development of ispace is a four-wheel, skid-steer rover. The rover uses a simplified type of rocker-bogey system, in which each side's pair of wheels is linked to the body by a differential. For example, when the left pair of wheels rotates up over an obstacle, the right pair of wheels is forced down, and the body takes the intermediate angle in between. In this way, the negative affect of pitch and roll is minimized for small obstacle traversal and all 4 wheels maintain ground contact. This improves stability, mobility and reduces negative movements of the cameras and antenna.

The basic mobility concepts including wheel dimensions and type of grousers were proven in "sandbox" testing at SRL.

The rover can travel over obstacles which are larger than the 18 cm wheel diameter.

The rover's size is sufficient to host many sensors and payloads, but in the premiere mission, it includes:

- 2 redundant ARM-based main controllers
- Motor controller and motors
- Power Distribution Unit (PDU) and battery
- Inertial Measurement Unit (IMU)
- 4 cameras
- 1 time-of-flight camera
- Radio and "pop-up" antenna
- Four radiation dosimeters (supplied by JAXA)
- Static payloads (supplied by GLXP and Hakuto's main sponsor, KDDI)

II.ii Dual rover configuration

The dual rover configuration (Figure 2) consists of two rovers. This configuration was developed to explore skylights on the lunar surface. It will not be used in the Hakuto mission, but is planned for a future mission.

The smaller, two-wheeled rover is tethered to the four-wheeled. The tether provides power and data transmission, and the rover can be towed passively and operated intermittently. This allows the rover to be extremely small due to relaxed thermal constraints.

As a secondary rover, it also has all redundant components removed.

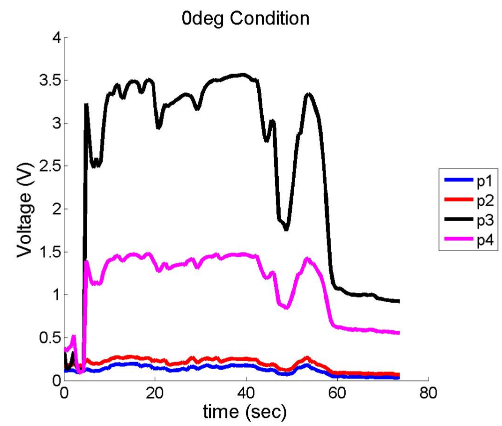

Fig. 1: Dual rover configuration

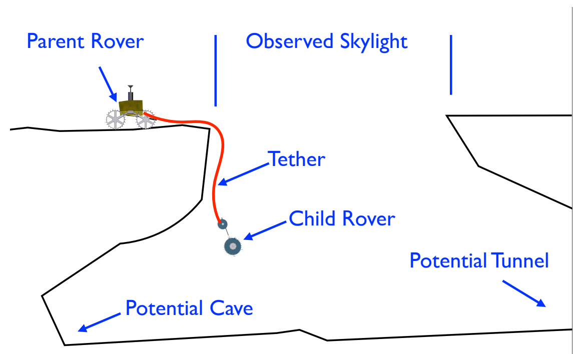

Fig. 2: Dual rover configuration

Figure 3 shows the "PFM" rovers in dual configuration.

Another potential mission configuration, now under development at SRL is several smaller rovers, creating a mesh network as they rove.

III. Iterative design

Sorato has undergone several iterations, summarized in Table 1. In this naming scheme, "EM" is "Engineering Model, "PFM" is "Pre-Flight Model," and "FM" is "Flight Model." Sequential numbering indicates smaller updates.

The rovers up until PFM2 and the concept for FM1 were developed primarily at SRL.[1].

Each iteration was made toward flight readiness and reducing mass and power budgets. The FM rover was designed to be flyable, but with a realistic expectation that ispace, a newspace company should gain design and qualification experience before the real mission.

Iterative design also allowed ispace to meet chang-

Fig. 3: Dual rover configuration with "PFM" rovers

Name	Date	Revised Items
EM	2010-13	Initial design
PFM	2013-14	Structure and electronics
PFM2	2015-16	Electronics
PFM3	2016	Thermal coating
FM1	2016-17	Thermal, structure, electronics
FM2	2017	Mass-down and latitude range upda

Table 1: Timeline and naming scheme of ispace rovers

Name	Date	Mass (kg)	Power (W)
EM	2010-13	10	30
PFM	2013-14	7.5	22
PFM2	2015-16	7.0	18
PFM3	2016	7.0	18
FM1	2016-17	4.5	15
FM2	2017	3.8	13

Table 2: Mass and power consumption reduction of ispace's four-wheeled rover

Fig. 4: "EM" rover

ing requirements as the lasnding site was changed. Until FM1, the rover was optimized for a 45 degree latitude landing site, although the design worked for a range from 35 to 55 before suffering from limitations due to the thermal environment.

The landing site selected for Team Indus is lower than 45 degrees latitude, so the FM2 rover is updated for optimization at a lower latitude.

The final, FM2 design is 3.8 kg. An additional mass of approximately 1.2 kg is required for the "interface" which attaches the rover to the lander, as well as the lander-side radio, wiring and fasteners.

III.i Mass reduction and power consumption reduction over time

The mass and power consumption reduction of the four-wheeled rover over time is shown in Table 2.

Figure 4 through Figure 8 show the progression of the rover.

PFM1 was the first design with an architecture designed for flight including an FPGA-based controller, 800 Mhz ARM image processor and a 360 degree, parabolic camera-mirror system. The experience of PFM1, especially postive results of the ARM processor in radiation environmental testing led ispace to change the architecture.

PFM2 used two redundant ARM processors. The redundant philisophy was carried throughout the architecture, and the single camera-mirror was changed to four cameras, arranged in a way to maintain 360 degree visibility. Removing the tall mirror was a key point to reduce the overall dimensions of the rover to reduce the final mass.

Mass reduction was obtained by iterating the structure design several times according to simulation and vibration testing results.

15 W power consumption of FM1 was determined using simulated bandwidth (50 to 100 kbps) and round-trip delay (5 s) conditions. Movement by teleoperation is limited by image quality. The relatively low quality 1 frame-per-second images obtained using this bandwidth result in about 90% decision making time (the rover only moves 10% of the time).

Small improvements in motor efficieny for FM2 allowed the power budget to be dropped to 13 W and the number of solar cells to be reduced from 50 to 38. This in turn has a positive affect on mass budget, thermal requirements and latitude range the rover

Fig. 5: "PFM" rover

Fig. 6: "PFM2" rover

can operate in.

The FM2 rover has not been publically unveiled yet.

IV. Qualification testing

Qualification testing was performed at each stage. Qualification testing philosphy is described in previous[2] papers.[3]

Throughout the iterations, radiation testing was crucial to screening and qualifying electronics to reduce power consumption over time. Components and systems were screened to survive a total dose of 22 krad, and systems were designed and screened to tolerate single event testing at 70 MeV, primarily through overcurrent detection and protection from damage by power-cycling.

In summary, the FM1 rover passed:

- Total dose radiation testing to 22 krad

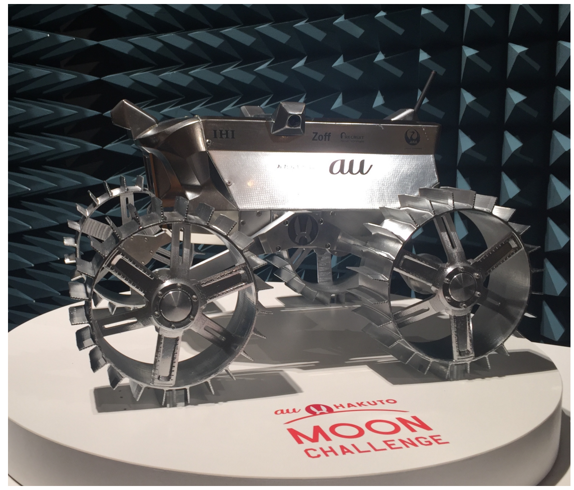

Fig. 7: "PFM3" rover

Fig. 8: "FM1" rover

- Single event radiation testing to 70 MeV including power system response to reset system before SEL-induced damage occurs
- Thermal-vacuum testing for cruise and surface mission phases (operational testing and simulation verification) to verify thermal design and heater requirements
- Vibration testing (sine sweep to 100 Hz with 20 G load level)
- Radio and antenna testing to confirm operation at 300 m from the lander

V. Design of the FM2 rover

The FM1 rover was designed for 45 degrees latitude, for operation throughout the lunar day, from 35 hours after lunar sunrise.[4]

Before manufacturing the FM1 rover, the landing site was updated to 35 degrees latitude but it was determined that the thermal performance was adequate, so manufacturing and qualification was not delayed to update the rover. The FM2 rover was updated for optimimum performance at latitudes as low as 28 degrees.

V.i Flight system architecture

Figure 9 shows the flight system architecture for Sorato.

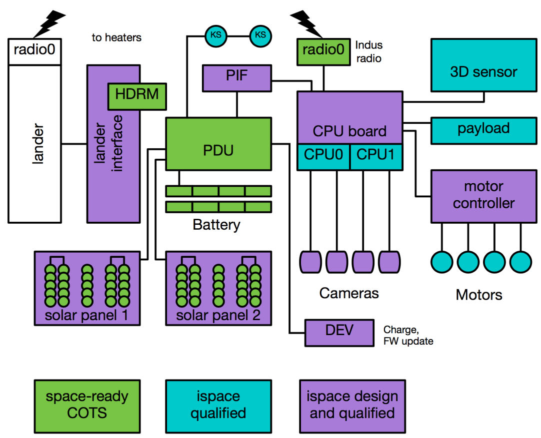

Fig. 9: Flight system architecture of Sorato

Aside from the space-heritage solar cells, and power distribution unit and battery, which are off-the-shelf cubesat components, all aspects of the rover are designed in-house using carefully screened terrestrial COTS components and manufacturing technologies.

V.ii Flight model structural design

Figure 10 shows the general thermal design.

The structural and thermal design of the rover and the "interface" which connects it to the lander meet the following requirements and concepts:

- The proven mobility of ispace rovers is maintained
- The number of actuators and parts in general is minimized
- The rover is held below the lander deck of the Team Indus lander
- The rover is thermally isolated from the lander, and its electronics are heated locally during cruise

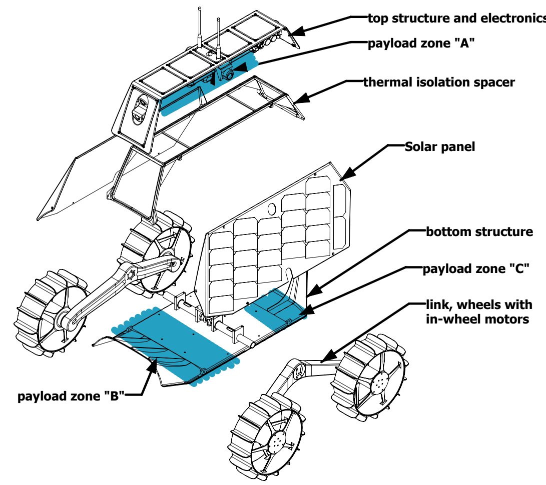

Fig. 10: Thermal design of the rover

- Power generation is maximized by choosing the side angle (no actuation)
- Electronics are mounted on top of the rover, directly to upward-facing radiators. Although this isnot ideal from a center-of-mass point of view, this minimizes overall mass and places the mass of the rover directly against the lander deck, allowing it to meet stiffness requirements with low mass.
- The electronics are thermally isolated from the solar panels
- The rover is isolated from lunar surface temperature
- During the surface mission, orientation of the rover is not limited, even without active thermal control

V.iii Flight system detailed thermal design

The battery is limited to a range of -20° to 50° C. Other electronics have a range of -40° to 85° C or wider.

The electronics are on top of the rover, and thermally isolated from the "hot zone", which comprises the solar panels, bottom, legs and wheels.

The radiators are covered in a silver teflon OSR. During cruise, the entire system is thermally isolated from the lander and local heaters for the battery and other electronics are used.

Although Sorato is designed for any orientation throughout the lunar day, in a contingeny plan, the rover's orientation can be used to control temperature

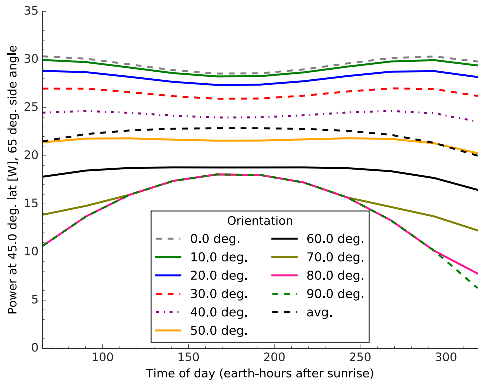

Fig. 11: Rover power generation at all rover orientation angles and time of day, at 45 degrees latitude

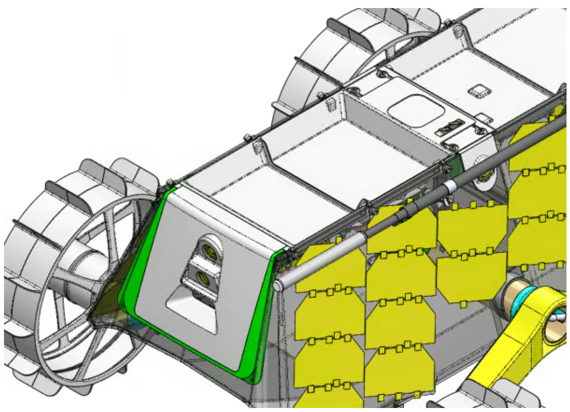

Fig. 12: Detail of the radiator for morning warming

somewhat, for example to limit temperature during lunar noontime.

In order to survive cold temperatures of the morning, a novel shape was added to the radiators in FM2, as shown in Figure 12.

The radiators were given a convex shape. The flat bottom with OSR is ideal to radiate heat away from the electronics during mid-day, but the sidewalls, without OSR, are heated by solar radiation when the sun angle is low. In this way, the temperature range was made narrower.

VI. Summary

The Sorato FM2 rover, which is the final flight model to complete ispace's GLXP mission, called Hakuto is now in the final phase of manufacturing and integration, after over seven years of iterative deisgn. The final rover is just 3.8 kg (plus about 1.2 kg of supporting equipment), uses only passive thermal design and able to operate without significant constraints throughout the lunar day at the latitudes of 28°to 38°.

VII. Work to be completed

The FM2 design, while not yet unvieled, is completed, with all electronics ready for integration, and structure manufacturing underway in parallel with rover integration, which has just begun.

To meet a short schedule, only two rovers are being integrated: a qualification/software test unit and a flight unit. At the component level, one rover's worth of flight spare parts are available.

After assembly The following items will be done with Sorato hardware from now until launch:

- QT level vibration testing (rover only)
- Thermal balance test for simulation confirmation
- Integration to the lander
- AT level vibration testing (with lander)
- Thermal balance test (with lander)

Software development will continue until after integration, with final unit testing, field testing and full mission simulation conducted in parallel with integration and hardware test activities.

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[1] J. Walker, "Scalable Flight System Design of Lunar Microrovers," PhD Thesis, Tohoku University, March 2016

[2] J. Walker, N. Britton, K. Yoshida, T. Shimizu, L. Burtz, A. Pala, Update on the Qualification of the Hakuto Micro-Rover for the Google Lunar X-Prize, Field and Service Robotics Proceedings, Toronto, Canada, July 2015.

[3] J. Walker, Qualification of a Dual Rover Architecture Including Deployable Cameras for Exploration of a Skylight on the Lunar Surface, 66th International Astronautical Conference, Jerusalem, Israel, September 2015.

[4] T. Oikawa et al, Thermal Design and Analysis of Conceptual Flight Model for a Lunar Exploration Rover, The International Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS 2016), Beijing, P.R. China, June 2016.