Development of Planetary Exploration Rover with Advanced Mobility and Intelligence

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Abstract

This paper describes an introduction of an exploration rover prototype and a field experiment with it at a lunar and Martian analogue terrain. The self-sustainable system of the rover consists of several subsystems, mobility, navigation, electrical power, sensor, communication and data handling, allowing it to perform end-to-end operations. In the field test, the mobility performance on rough terrain is mainly verified with obtaining more than 50 states including stereo images; thus, the calculation and estimation, such as the visual odometry, skyline matching, path planning, and map construction, can be posteriori performed on the basis of the obtained data. Consequently, it is confirmed that the rover has the capability to travel more than 1 km for a couple of days and a new finding for a path planning is obtained.

1 Introduction

Mobile robots and rovers have been increasingly employed for the scientific mission on lunar, planetary and the earth surface explorations. The rovers are capable to move on a natural terrain by using mechanisms such as rotating wheels, [1][2] hopping mechanism by using reaction wheels, [3] and walking mechanism with ski boards [4]. By using these moving mechanisms, the rover performs science or utilization missions that are collecting sample, locating sensor, excavation and insitu analysis in wide area. In a motion control of a planetary rover on loose regolith, it is a important issue to reduce positioning errors due to various nuisance such as wind, dust storm, soft terrain, steep, slope, rough, failure of a instrument, and structural vibration. Moreover, the traveling speed of the planetary rover is typically slow [5]. Thus, a robotic manipulator [6], an entry probes such as a penetrator [7], and an unmanned autonomous vehicle like an airplane [8] are also employed as a scientific probe; recently, the casting manipulator [9] can be provided for the quick and wide range mission. Therefore, it is important to appropriately select a probe with depending on range and operation time, as shown in Table.1.

“AKI”, the rover with Advanced Kinematics and Intelligence, shown in Fig.1, is the rover prototype developed in order to demonstrate mobility, autonomous or semi-autonomous navigation with a manned/unmanned operation, implement more accurate and robust recognition for external and internal states, and wireless power transmit required for a future exploration mission. This paper presents the introduction of the technologies employed for the rover and the results derived from the field experiment conducted at a scoria-covered rough terrain; thus, we show that high-performance rover is available for any mission to scientifically observe and operate.

This paper is organized as follows: the section 2 introduces the system overview of the rover prototype; the section 3 describes the experimental results.

2 System overview of AKI

The appearance of hardware components of AKI is shown in Fig.1; and it can be divided into the subsystems, such as mobility, electrical power, sensors, navigation and control, and data handling. These subsystems enable AKI to be a self-sustainable and perform several experiments in the field. Table 2 summarizes the specification of the rover. The details of part of the subsystems are described in this section.

2.1 Mobility subsystem

AKI has four independently driven wheels, having a diameter of 0.20 m and a width of 0.15 m. The circumferential surface of the wheel is covered with the silicone rags, which enable the wheel to firmly grip the ground and increase its traction force. The actuator for the wheel consists of the DC brushed motor, Maxon RE25 (20 Watts), with encoder for the measurement of wheel rotational angle and the double-stage gear which is comprised of a planetary gear (19:1) and a harmonic drive (80:1). The maximum cruising velocity is approx-

Table 1. : The optimal science probes depending on operation time and range

Optimal probes		Operation time		
		Short	Middle	Long
Range		< a day	< a week	≥ a week
Short	< a few meters	Manipulator	Manipulator	Manipulator
Middle	< several hundred meters	Casting	Casting	Rover
Long	≥ several hundred meters	Plane*	Plane*/Rover	Rover

*...only in air on the planet such as Mars and the earth

imately 0.07 meters per second and the rating force generated by the wheel is more than 200 Newtons with considering efficiency. The motor is driven in the PWM rated voltage with a trapezoidal shape which is adjusted with considering the simultaneous suppression of sinkage, slippage and vibration [10].

All the wheels have active steering degrees of freedom. The steering actuator consists of the DC brushed motor, Maxon RE25 (20 Watts), with the potentiometer, which measures the absolute steering angle, the cross roller bearing, which strictly supports the rotational axis, and the double-stage gear which is comprised of the planetary gear (71:1) and the harmonic drive (80:1). Thus, the steering unit implements that the rated rotational speed is approximately 10 degrees per second and the rating torque for steering wheel is more than 80 Newton-meters with considering efficiency.

The four drive-and-steering units are connected to the separation via the Load Equalization Pulley Suspension (LEPS). LEPS is a mechanical passive suspension that connects all the legs by a wire made of synthetic fibers. LEPS is employed to suppress change of the attitude of the main body when climbing an obstacle such as a rock and a bump, as shown in Fig.2, and to keep the identical normal forces of all the wheels against the soil; thus, the suspension can reduce mobility hazard such as vehicle rollover and increase the efficiency for traveling on loose soil. Further, the main body and legs can be easily separated at the separation, in order to enhance the usability.

2.2 Electrical power subsystem

The electrical power subsystem simply consists of the single rechargeable battery unit, the control unit for bus power supply and voltage regulation. The battery unit contains 8 rechargeable lithium-ion cells of 9.8 Ah in series. The battery unit run out in 3~4 hours with continuously supplying the power required for the rover components, without the other power supplies by SAPs and wireless power transmission. The power control unit supervises the power from the batteries and supplies it to the on-board computers, sensors, communication devices and actuators. The technical detail of the electrical power subsystem has been reported in [11].

2.3 Communication subsystem

Telemetry, tracking, and command from/to the rover are handled via a wireless LAN communication system in 2.4 or 5.8 GHz band. The wireless LAN router connected to Ethernet HUB and two whip antennas with a low gain. The ideal data rate is 54 Mbps and the fact of the maximum rate is approximately 20 Mbps, but this varies along with the distance between the rover and a base station at which an operator(s) monitors the data. The reachable distance of the communication is experimentally confirmed as approximately 900 meters with 6.5 Mbps.

2.4 Data handling subsystem

The rover possesses a single On-Board Computer (OBC) based on the embedded CPU, SH–4, with an interface board which has analogue and digital IOs. OBC is employed for the control of motors with a short cycle and utilized for the various tasks with a long cycle: acquisition of House Keeping (HK) data, resource (time, power, data) management, and error check, parameter setting. The images captured by a camera and almost all of the HK data are temporarily stored in the two data loggers with 24 bit A/D converters and independently transfered to the computer in the ground station via the wireless communication. The DC brushed motors, for pan-tilt mechanism, and driving and steering wheels, are controlled by OBC and motor drivers; the Inertial Momentum Unit (IMU) also directly connects to the OBC system. All the computers including the data loggers are connected each other with asynchronous communication via Ethernet and the wireless network.

2.5 Sensor subsystem

A lot of sensors, acceleration pick-up, inclinometer, MEMS gyro, GPS compass, Sun sensor, encoder, potentiometer, optical camera, laser range finder, voltage sensor, current sensor, temperature sensor and GPS receiver, is installed in the rover system. After the sensor data is acquired and converted with a A/D converter and

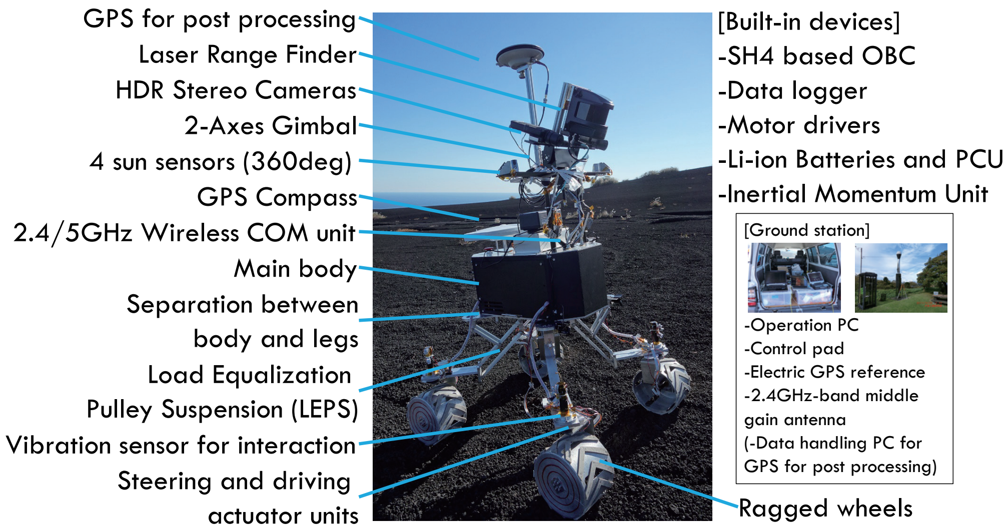

Figure 1. : Detail of the rover with advanced mobility and intelligence

Figure 2. : Closeup for LEPS suspension

serial communication device in the data handling processor, the states of the rover, time (rover local time, absolute time), attitude and angular velocity (roll, pitch, yaw), orientation, position and acceleration (relative, latitude, longitude, Altitude), vibration acceleration of legs, absolute/relative rotational angles and angular velocities for motors, temperature, resource amount and state (current, voltage, power, data), and communication rate, are calculated in the on-board computer and the ground station.

Further, the High Dynamic Range (HDR) camera pair for acquiring images, sun sensor for position of the Sun, and LRF (Scanning type) for measuring shapes of obstacles and terrain are also attached to the top of a mast in the rover system; particularly, the camera pair and LRF are installed on the pan tilt gimbals, which rotate within tilt of ±90 degrees and pan of ±180 degrees and whose attitude is measured by not only the encoder and potentiometer in the actuators but also the 2-axis inclinometer located in the vicinity of the camera and LRF; in addition, the heading direction of the pan actuator in the gimbals would be measured with high resolution by using the modulated wave resolver, shown in Fig.3, which has high resolution is more than 0.25 million split per one rotation and can be utilized in wide thermal condition (-200–+200 degree of Celsius) and severe radiational environment (¡ 20 Mrad). Moreover, the HDR camera has wide dynamic range 120 dB and can take an image in low-light environment with less than 0.1 lux; thus, it can reduce appearance of the rest white and black in an image due to light condition; the clear images is then obtained as shown in Fig.4, even if including the shadow of the rover and the direct sunlight. The cameras have Ethernet interface and the resolution of image which is nominally 1280×960 pixels. LRF provided by Hokuyo Automatic Co., Ltd. enables 2-D scanning with the range of ±95 degrees. The resolution angle of the 2-D scan is a quarter degree. The maximum reachable distance of the laser is experimentally confirmed as approximately 60 meters. Three dimensional terrain features can be obtained by simultaneously tilting the LRF head by the gimbals while the LRF scanning 2-D plane. On the basis of the converted data above, the autonomous and tele-operation are performed.

Here, GPS receiver is employed only for evaluation of the rover position; accuracy of the measured position is less than several centimeters and that is implemented by post-processing based on GPS data from the base station in the field and the GPS Earth Observation Network System (GEONET) out of the field.

Table 2. : ”AKI” system specification

Physical	
Mass	50 kg (Approx.)
Dimension	0.88 m × 0.83 m × 1.5 m
Mobility	
Wheel	0.20 m (diameter) × 0.15 m (width) Lugs: silicone made Actuator: DC brushed motor
Velocity	0.07 m/s (max)
Power management & control	
Battery	Single 8 Li-ion in series (9.8 Ah in total)
Bus power control	Unstable 28 V bus power supply, regulated to 24, 12, 5, and 3.3 V
Communication	
Device	Wireless Ethernet with low gain whip antennas (2.4 / 5.8 GHz band)
Max. data rate	54 Mbps (ideal), 20 Mbps (fact)
Sensor	
Absolute position	Double frequency GPS (for post processing),
Attitude/Orientation	3-axis acceleration pick-up, 3-axis gyro, GPS compass, 2-axis inclinometer
Attitude of gimbals	Potentiometer, Encoder, Exclusive 2-axis inclinometer
Vibration of legs	Double 3-axis acceleration pick-up,
Environmental status	4-sun sensors,
Navigation	High Dynamic Range (HDR) camera pair, Laser Range Finder (LRF)
On board computer	
HK data handling	Single 600 MHz SH-4, 2-data logger running LINUX, Windows Embedded CE
Navigation	
Motor control	
Operational mode	Direct tele-operation, Autonomous

2.6 Other subsystems

Regarding the structure of the rover, the main body is made of CFRP and aluminum, mobility frames are also made of aluminum, and all the electrical boxes, including data processors, DC-DC converters and so on, are made of aluminum and fixed to the main body by using stainless or PEEK screws.

Thermal control in the rover system is implemented by the passive devices; the temperature of the battery is always monitored, and the heat from the instruments is exhausted through the aluminum cases to the bottom and side of the main body.

3 Field experiment

The field experiment with the rover prototype is conducted on a scoria-covered field in volcanic region of Tokyo, Japan. The field consists of sloped terrain, ditch, vegetations, and rocks . In the field experiment, the mobility performance on rough terrain is mainly verified with obtaining more than 50 states including images, as shown in Fig.5; hence, the calculation and estimation using images by HDR camera pair and LRF, such as the visual odometry, skyline matching, path planning, and map construction, are posteriori performed.

Figure 3. : Photo of modulated wave resolver with extreme high resolution and environmental resistance

Figure 4. : Photos taken by HDR camera

Consequently, from the experiment conducted at the scoria-covered rough terrain, the mobility performance of the rover is confirmed as the rover has the capability to travel more than 1 kilo-meters for a couple of days. Figure 6 indicates the trail of day trip by the rover on the field. The rover can also negotiate with obstacles, the size of which is as large as the wheel diameter; in addition, the slope angle of the terrain is 0.24 degrees in average; however, the maximum is 22 degrees and the standard deviation is 7.5 degrees; that is, the rough terrain with large bumps covers the field.

The energy loss to compensate the gravity force due to the pitch motion of the rover is approximately 20 kJ, which is calculated on the basis of the multiplication of the gravity force, mass of the rover and climbing slope angle except for constant energy in the case that the rover travels on a flat surface and the computer always works. Further, the average power is increased up to 2.5 Watts; however, the maximum power increase is 13 Watts as compared to the power during travels on the flat surface. Thus, the power regulation system should be designed with considering the maximum power of the motion and constant power consumption by computers and peripherals.

Meanwhile, AKI has no solar array panels; however, it is assumed that the panels with the 0.8 m^2 surface area and 10% efficiency are installed to the rover; the loss

Figure 5. : A scene of the field test in volcanic region

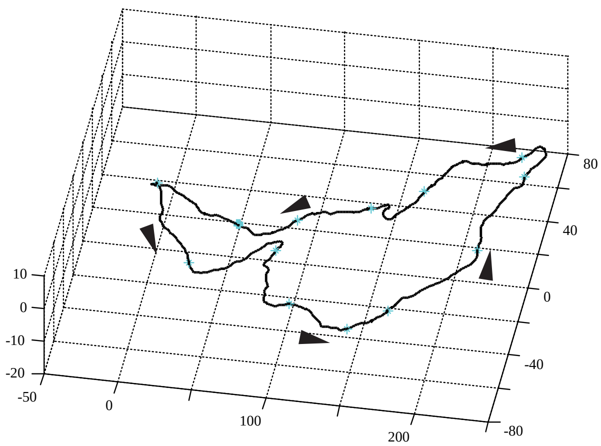

Figure 6. : Trail of day trip by the rover in the field test

of the energy generation, due to the yaw motion of the rover, is 210 kJ, which is estimated on the basis of the cosine loss of the power generation subjected to change of the relative attitude of the rover to the Sun. As these results, it is found that the rover should preferentially control its yaw angle from the viewpoint of the power generation and resource reduction; naturally, the additional power generation induces high temperature. If efficiency of the power generation was increased by a yaw control, the area of solar array panels would be smaller and the rover would not be care of the maximum power increase due to the motion; that is, the entire mass of the rover is then reduced. From the viewpoint of a path planning, rather than consideration of the terrain, consideration of the amount of power generation should bring higher efficiency to the rover.

4 Conclusion

This paper described the introduction of the planetary exploration rover prototype and the result of the field experiment with it at a lunar and Martian analogue terrain. The elemental technologies of the rover AKI were also introduced and it was confirmed that they are based on the novel technology. In the field experiment, the mobility performance on rough terrain was verified with obtaining more than 50 states including stereo images; consequently, it was recognized that the rover has the capability to travel exceed 1 km within a couple of days; further, the data set for the posteriori calculation was obtained. Finally, it was confirmed that the path planning with considering the amount of power generation provides a lot of benefits to the rover.

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