ROBOMECH Journal
a SpringerOpen Journal

RESEARCH ARTICLE Open Access

Study on grouser mechanism to directly detect sinkage of wheel during traversing loose soil for lunar exploration rovers

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Abstract

The rovers, which some researchers and agencies are developing, have many functions to sense a lot of information from peculiar environments like the lunar surface for localization, path planning and so on. On rough terrain, without artificial ground maintenance, like the lunar surface, the rovers avoid obstacles by using sensors, which they have.

However, if the rovers traverse loose soil, like the planetary surface, there exists the sinking behavior. This sinkage is caused by the weight of the rover. At present the rover sensors are unable to sense it. Actually, Mars Exploration Rover (MER, NASA/JPL), during its exploration on Mars, was disabled because of this. If MER could have known the subsidence of each wheel in time, MER may have avoided this catastrophic condition.

We therefore propose to have the grouser mechanism, which can detect sinkage of the wheels of rovers, installed on the wheels of rovers. The grouser mechanism is needed to traverse loose soil like lunar surface and mars surface. When the wheel rotates on loose soil, the resistance force from the loose soil is given to the grouser. However, initially, for the wheel contacts on the surface of loose soil, the resistance from the loose soil is small. We will develop the grouser mechanism with a function that can detect the whole range of the effective resistance force from loose soil including this small resistance force.

This study moreover carries out experiments with various loads and verifies the effectiveness of the proposed mechanism, using pictures, of contact with the loose soil surface.

Keywords: Sinkage; Grousers; Wheel; Loose soil; Lunar rovers

Background

Robots are among the most important mission systems for planetary exploration. These robots are designed to travel along planetary surfaces to gather precise information regarding, among other things, the origin of the solar system [1]. The NASA Mars mission in 1997 utilized the micro robot Sojourner, which moved about and explored the surface of Mars, transmitting important data and detailed images of the Martian surface back to Earth [2]. The Sojourner mission demonstrated the importance of mobile exploration. In 2003, NASA/JPL sent Mars Exploration Rover (MER) to Mars, which also transmitted important data [3].

Planetary exploration rovers are required to traverse rough terrain such as those found in craters and cliffs, which are scientifically important locations for exploration. Rovers are required to travel over these rough terrains and must avoid tipping over and becoming stuck. The surface of the Moon, which is the target of this study, is covered with regolith that is soft and slippery. This regolith, which is made up of fragments of rock broken from the moon and other celestial bodies, undergoes chemical changes caused by the granular phenomenon. As this regolith is different from weathering soil on Earth, a conventional wheel would not achieve the necessary traction efficiency for movement on this surface. The lunar environment is a vacuum and is exposed to radiation from space. Moreover, the temperature differences between day and night are intense. In such environments, conventional tires, meant for use on Earth, cannot be used. Therefore, wheels made

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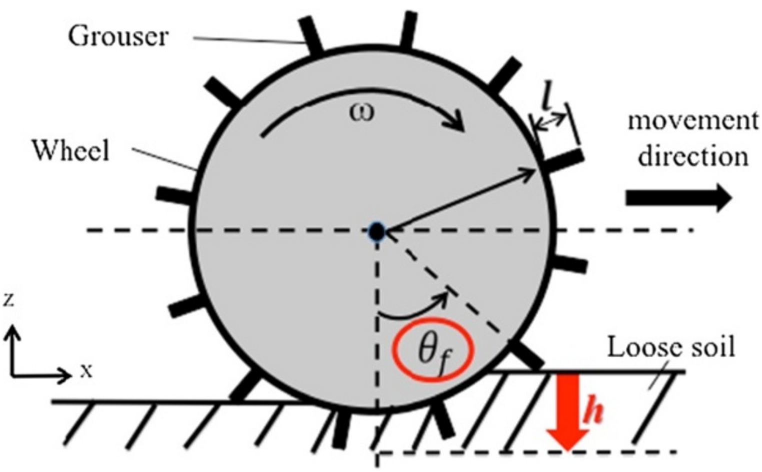

Figure 1 Interaction between wheel with grouses and loose soil.

of a rigid material, such as metal, are used for lunar and Mars rovers.

The problem is, when a rover with rigid wheels traverses loose soil, there is a possibility of extremely bad traction conditions. This means that slipping and sinking behaviors can occur. The wheels of the MER was sinking into the soil and could not move; a situation that is not easily rectified. When the rovers are traversing loose soil, we have to consider the condition of the ground under the wheels. The relation between the wheel and loose soil can be described using Terramechanics [4]. Using terramechanics, the entrance angle, which can indicate the depth that the wheel is sinking into the soil, is used to lead the drawbar pull. Many researchers are studied about Terramechanics [5–8]. Ding et al. summarized the most recent work on Terramechanics [9]. It is necessary to understand the range of the contacting angle between the wheel and loose soil for the derivation of drawbar pull. The contacting angle is shown using the entrance angle and the leaving angle. If the entrance angle can be detected while the rovers are traversing, the drawbar pull and the sinkage can be derived "real time". It is effective to detect sinkage to determine the rovers moving path.

The poor traction conditions can be avoided if the entrance angle is known while the rovers are traversing loose soil. Some research has been performed to acquire the range of contacting angles between the wheel and loose soil. A.Krebs et al. developed a flexible wheel with tactile sensors [10]. They used IR distance sensors to detect the contacting angle between the flexible wheel and the ground. Nagatani et al. developed a wheel with a built-in force sensor array (containing many sensors on the surface of the wheel) that can measure the normal stress distribution [11]. This study focused on the grousers mounted on the surface of the wheels. When the grouser touches on the surface of loose soil, it can acquire the resistance force from loose soil. If we can acquire this information, the sinkage can be predicted. However, the

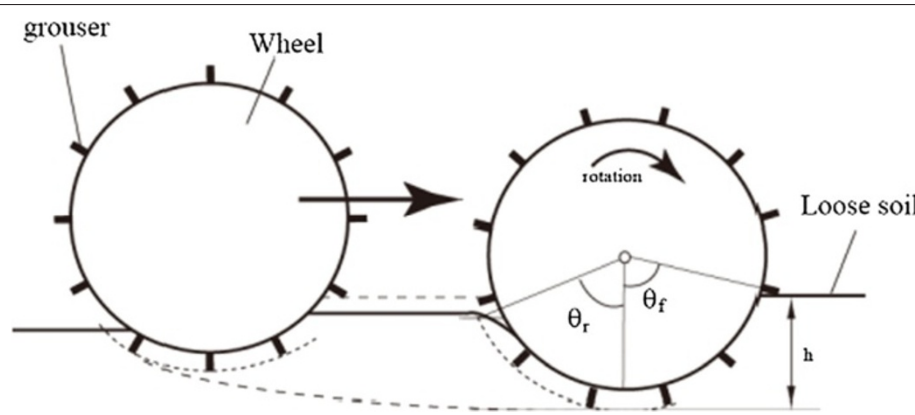

Figure 2 Dynamic condition of sinkage of wheel.

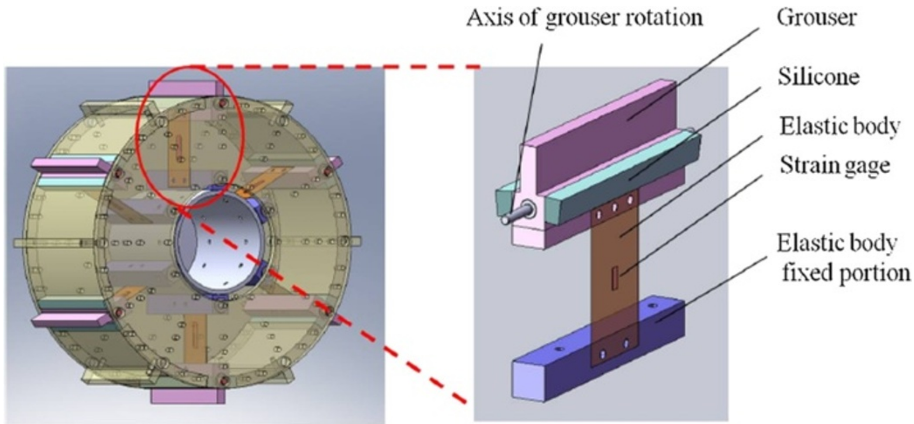

Figure 3 Proposed wheel with grouser mechanism which can acquire concrete information from the loose soil.

resistance from loose soil in the first place is very small [12]. We need to consider the grouser mechanism with a function that can pick up the small resistance force from loose soil immediately at touching. This paper proposes the grouser mechanism to detect immediate information at the first touching of loose soil. The proposed mechanism consists of the principle of leverage and supposes that the small resistance force can be acquired at the moment of touching the surface of loose soil.

In this paper, we will present a developed wheel with grousers, which have tactile sensors to calculate the entrance angle. Firstly, we mention the sinkage of the wheel with grousers. Secondly the proposed grouser mechanism is explained. Then the experimental device and condition are mentioned. Finally, we will give the conclusions of the study after the results and a discussion are presented.

Sinkage of wheel with grousers on loose soil

The sinkage of the wheel while traversing loose soil can be calculated by using the conventional terramechanics model [4]. When the weight of the wheel is given at first, the normal stress can be calculated as static condition (not dynamic condition). The entrance angle and the exit angle are given when the value between the weight of the wheel and force calculated by using the normal stress is equal [13]. However, there are some problems with that situation. The sinkage including the height of grousers is not contained in this calculation using the conventional terramechnics model. The sinkage is not known by the dynamic condition. The wheels for rovers have installed some grousers to get the effective driving force on loose soil. So, the sinkage including the height of grousers and the dynamic situation are needed to understand this. Some researchers have considered the

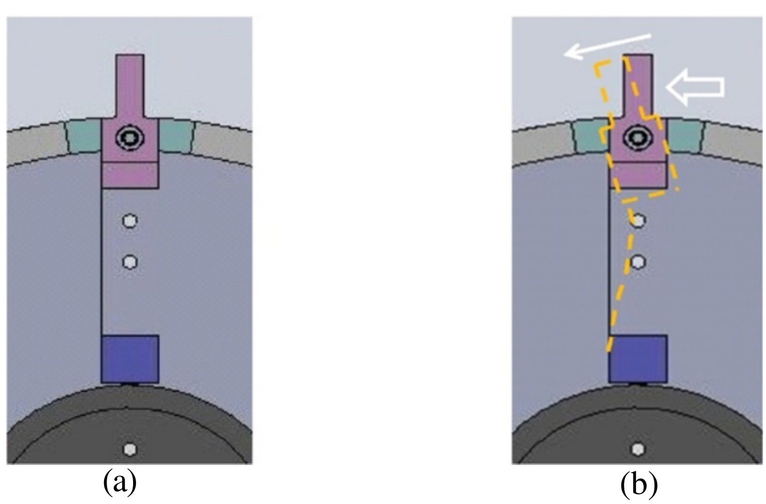

Figure 4 Grousers mechanism with "lever rule". (a) Before without supplying some load. **(b)** During supplying some load.

Table 1 Characteristics of strain gage

Descriptions	Value
Size	15*5*0.1 mm
Gage factor	1.98 ± 0.1%
Gage resistance	120.4 ± 0.4 ohm
Adapt linear expansion coefficient	1.9 *19^{-6} / °C

running situation using wheel with "grousers". Ding et al. and Sutoh studied the influence of grousers experimentally [14–16]. The sinkage is measured by using some extrinsic sensors, for instance motion capture and the rotary encoder and so on. This means that the wheel cannot calculate its own sinkage in time. From this problem, this paper suggests a wheel that can measure the sinkage directly.

Figure 1 shows the interaction between the wheel with grousers and loose soil in static conditions. The entrance angle θ_f is changed due to the presence of grousers. If the wheel does not contain grousers, the sinkage is written as follows:

$$h = r(1 - \cos\theta_f) \tag{1}$$

On the other hand, if the wheel contains grousers on its surface, the sinkage is written as follows:

$$h = (r + l)(1 - \cos\theta_f) \tag{2}$$

Figure 2 shows a dynamic condition of sinkage of the wheel. If the wheel has a rotation movement on loose soil, the sinkage of the wheel increases gradually. If we can obtain the value of sinkage during a real operation, we can prevent the wheel from becoming stuck. When

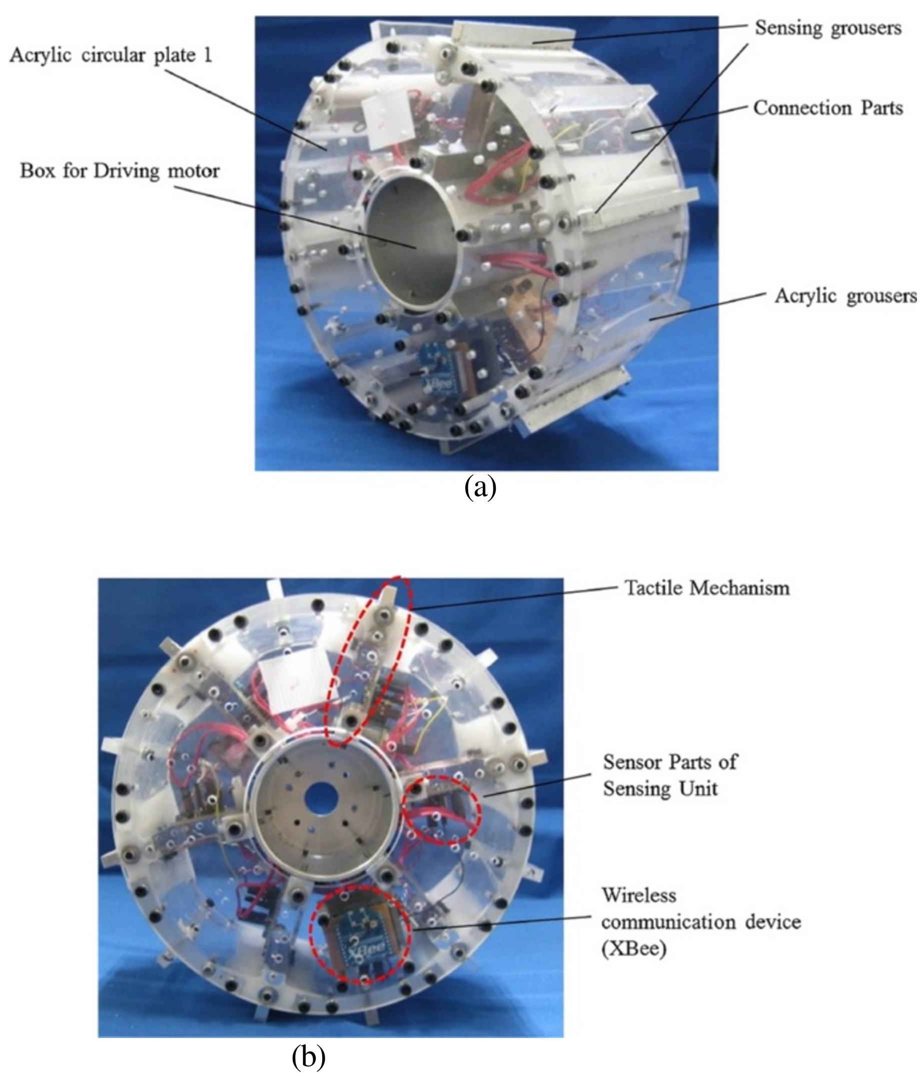

Figure 5 View of proposed wheel. (a) Side view. **(b)** Front view.

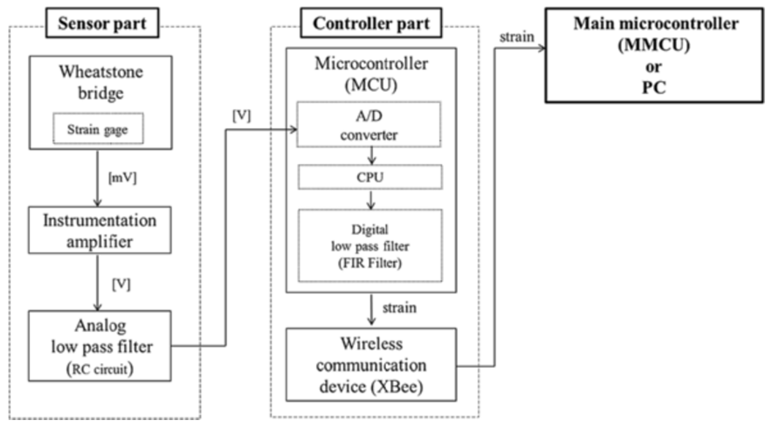

Figure 6 Detection flow of data from strain gage.

the wheel is rotating on loose soil, the grouser mounted on the surface of the wheel contacts loose soil. If the values of the wheel radius, r, the length of the grouser, l, and θ_f are known, we can predict sinkage, h, in real time. If the grouser contacts the surface of the soil, we can obtain the entrance angle θ_f. Grouser with the incorporated tactile sensor is described in the next section.

Methods

Detection mechanism using grousers

We previously mentioned the advantages of the ability of a grouser that can get information on contact. This wheel needs to have grousers that have a very sensitive detection function in order to calculate accurately the resistance force from the soil. Figure 3 shows the proposed mechanism to detect this information between the grousers and the surface of loose soil on contact. The grousers are connected to the elastic part that exists inside the wheel via the axis mounted on the surface of the wheel. The strain gages are mounted on both surfaces of this elastic part. The grousers are made of aluminum and the elastic parts made of beryllium copper. When the resistance force from the soil is given to the grousers on contact, it has some rotational movement. This movement means that the elastic part takes some strain. There is a difference between the height of the grousers and the length of the elastic part. The displacement becomes larger since the length is longer than the height of the grousers (Figure 4). If the displacement of grousers is large, the performance of this wheel will change compared with the rigid wheels with their rigid grousers. Apart from this, our proposed wheel has the same performance as the rigid wheel. This means that the displacement of grousers is short. But the wheel can get the large strain value. The large strain is better to detect the condition on contact. The strain gage resistance value changes when the strain gage is warped, and we can convert this resistance value (voltage) to a strain value. Table 1 shows the characteristics of the installed strain gage [http://www.kyowa-ei.us/eng/index.html].

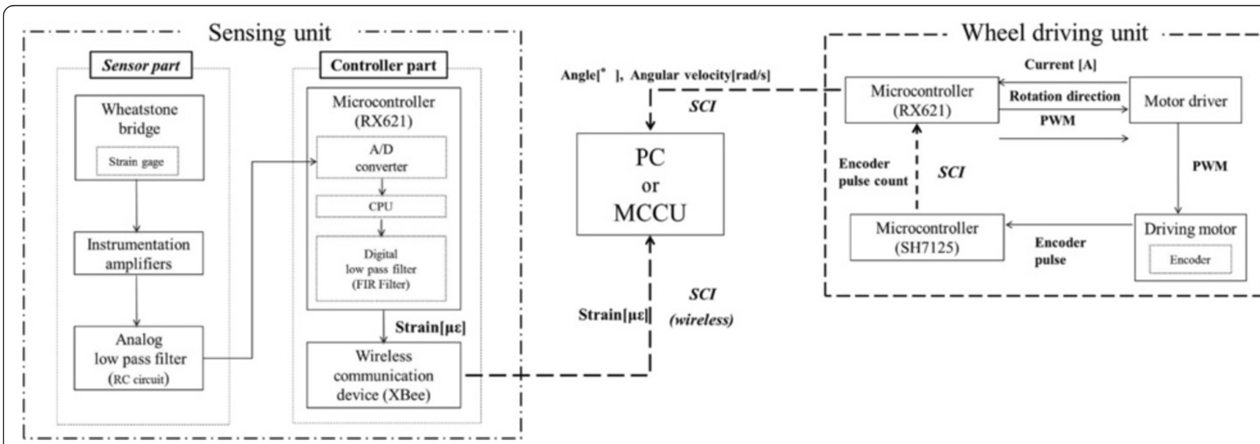

Figure 7 System flow of proposed wheel.

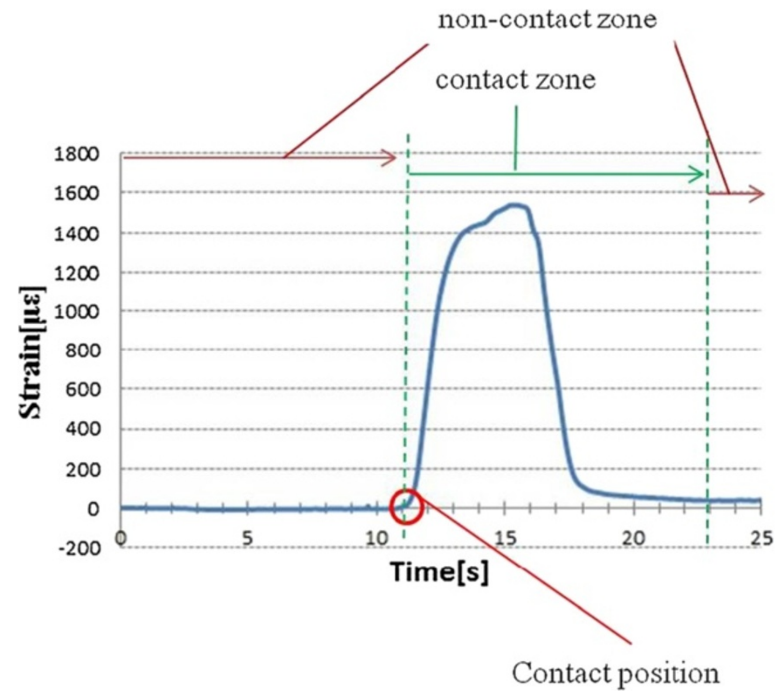

Figure 8 Sample data of strain.

Proposed wheel with grousers mechanism which can detect sinkage

The proposed wheel to detect sinkage is shown in Figure 5. The diameter of the wheel on which the grousers are installed is 200 mm and the width is 100 mm. The wheel, which is made from acrylic resin, contains 12 grousers spaced at 30° intervals. The box for the driving motor is made from aluminum. Both sides of the wheel are covered with the acrylic resin. Only 6 grousers of all the grousers have a function to sense concrete information. This is because the proposed wheel keeps performance same as rigid wheel. The proposed wheel hence can measure sinkage at 60° intervals. The height of the grouser is 10 mm and the width is 6 mm. The length is 100 mm as same as the width of the wheel.

A microcontroller (RX621) unit performs analog to digital conversions used to process the data from the strain gage, and is shown in Figure 6. A low pass filter (LPF) is used on the raw strain data, and the cutoff frequency was determined using a data logger (which was used throughout the experiment to measure strain) [17]. From these measurements, we set the cutoff

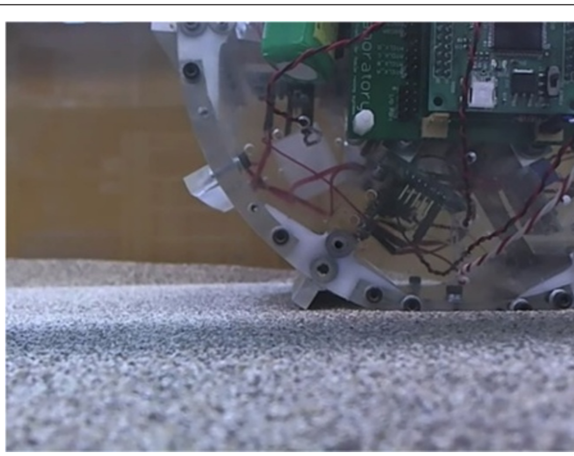

Figure 9 View of contacting wheel to loose soil.

Figure 10 Example view after image processing.

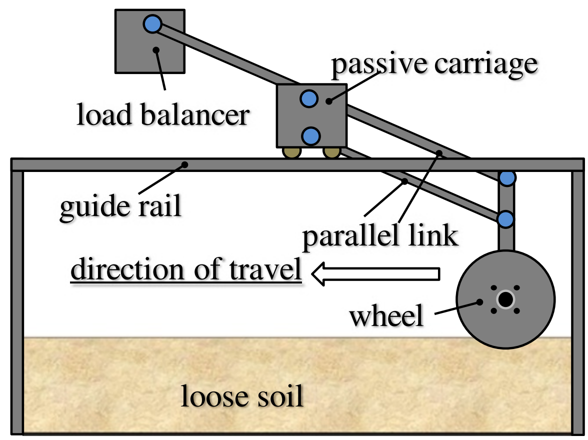

Figure 11 Experimental systems to traverse single wheel on loose soil.

frequency to 1 kHz. This data is sent to main micro-controller using a wireless communication device (Xbee).

System flow of proposed wheel

Figure 7 shows the system flow of the proposed wheel. After the strain value is firstly sent from gages as the value of the voltage, this data is exchanged to a strain value calculated by the RX microcomputer including a low path filter as mentioned above. The strain values are then sent to the main PC (for the wheel driving unit) using the wireless device (XBee). The strain data and the rotation angle of the motor, each time, is written as a CSV file.

The next section describes how to judge the angle where the grouser contacts the loose soil surface.

Table 2 Experimental conditions

Descriptions	Value	Unit
Angular velocity	0.1	rad/s
Wheel load	5, 10, 15	kg
Loose soil	Keisa No.5	-

How to judge the contacting angle to loose soil

The contacting angle of the grouser against the loose soil is determined from the value of the strain gage as shown in Figure 8. However, we need to understand whether the grouser actually contacts the surface of the loose soil. The pictures are taken at 10 Hz during an exercise where the wheel traverses loose soil as shown in Figure 9. Then, the modified pictures given by the image processing of each sample are used to judge the contacting angle as shown in Figure 10. We extract the picture that the grouser contacts the surface of the ground from the modified pictures given at 10Hz. It is determined whether the wheel touched the surface of the ground by a pixel unit.

Experimental device and condition

Single wheel test bed

Figure 11 shows the single wheel experimental test bed. Our research group has utilized to estimate various wheel until now [18]. The experimental system consists of mechanical parts and sensors, which connect the wheel with a tactile sensor to measure sinkage, as shown in Figure 12. A single wheel, a parallel link, a stator, a guide rail, and a load balancer were used in carrying out the various experiments. A parallel link was attached between the axis of the wheel and the load balance. We controlled the rotation of the wheel and measured the angular position using the wheel's motor encoder.

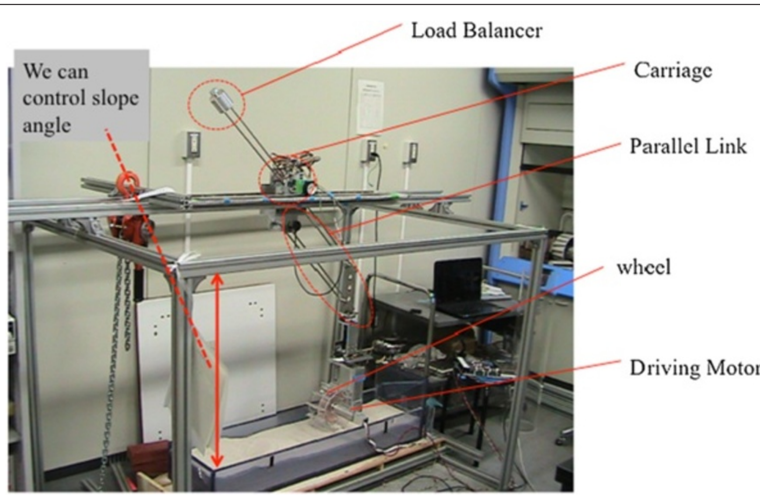

Figure 12 Overview of single wheel test bed.

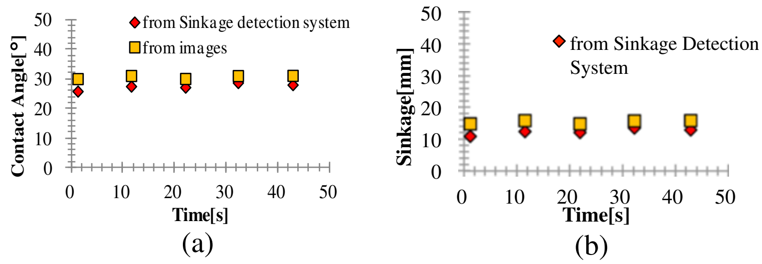

Figure 13 Contacting angle and sinakge (5 kg). (a) Contacting angle. **(b)** Sinkage.

Experimental condition

Experimental condition is shown as Table 2. The angular velocity of the wheel is 0.1 rad/s [19]. In experiments, we set the slope to 5, 10, 15 deg. Then, we use Keisa No. 5 (Japanese Industrial Standards Committee: JIS G5901-1974 [20]) [https://www.jisc.go.jp/eng/index.html] as loose soil.

Results and discussion

Figures 13, 14, and 15 shows experimental results using the contacting angle and sinkage. In the figures, the red points indicate the value of sinkage and the yellow points are the value calculated by image processing. Here, the yellow points mean the corrected value. In case of a wheel with 5 kg load, all data appears around 30 deg. The view of contact between the wheel and the surface of loose soil is shown in Figure 16. The correct values were detected using the picture after image processing. The detected values from proposed method are a value close to corrected values. The sinkage's values are a value close to the correct values too. In case of 10 kg, all data appears from 30 to 40 deg. The correct values were detected using the picture after image processing as in the case of the 5 kg (Figure 17). The detected values from proposed method are a value close to the corrected values as shown Figure 14. The sinkage's values are a value close to the corrected values too. In the wheel with 15 kg, all data is shown around about 40 deg. The correct values were detected using picture after image processing as in the case of 5 kg and 10 kg (Figure 18). The detected values from proposed method are a value close to the corrected values as shown Figure 15. The sinkage's values are a value close too. Interestingly, the contacting angle increases when the wheel's load becomes larger, along with the sinkage. These results verify that this proposed method could detect the varying sinkage and angle using a variety of loads.

Conclusion

The surface of loose soil is very soft and the shearing strength is nonlinear. Therefore, the wheel needs to detect the tactile information directly and sensitivity. On this paper, the proposed grouser mechanism mounted on the wheel could detect sinkage directly and a difference between the correct values and data of experiments using single wheel test bed that could traverse loose soil was very small.

The wheel with proposed grousers which can detect sinkage directly will be able to utilize as advanced applications, for instance as measurement systems to solve some problems (measurement of accurate entrance angle and so on) which are occurred between the wheel and the loose soil ("problems of Terramechanics"). In the near future, we will be able to suggest the rovers without the poor traversing condition that is caused by sinking behavior.

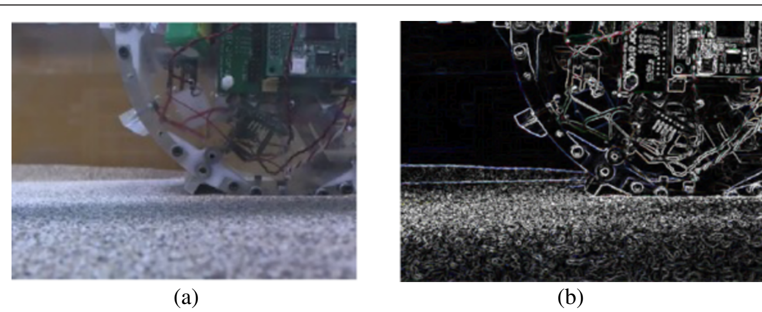

Figure 14 Contact view between wheel with 5 kg load and loose soil. (a) Before image processing. **(b)** After image processing.

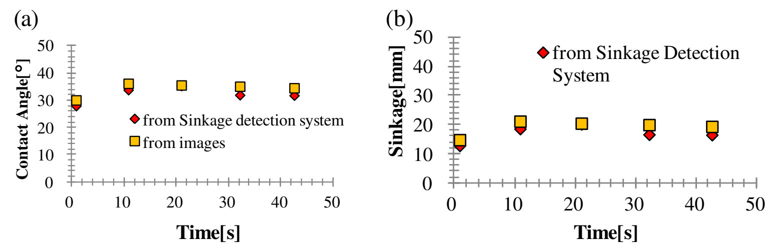

Figure 15 Contacting angle and sinkage (15 kg). (a) Contacting angle. **(b)** Sinkage.

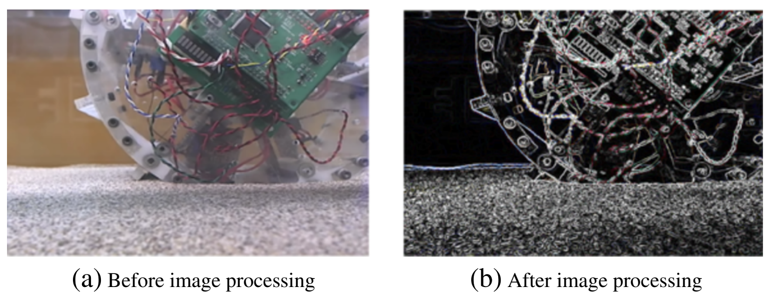

Figure 16 Contacting angle and sinakge (10 kg). (a) Contacting angle. **(b)** Sinkage.

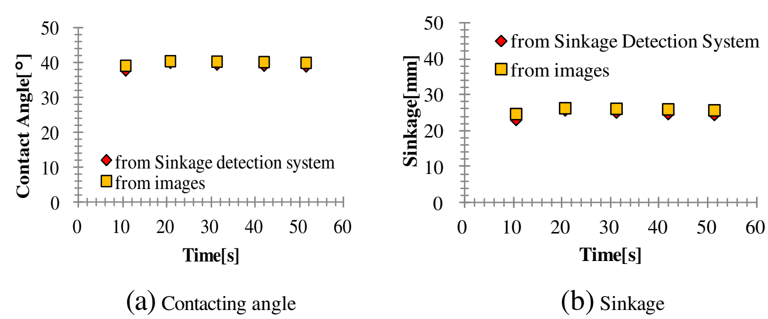

Figure 17 Contacting view between wheel with 10 kg load and loose soil. (a) Before image processing. **(b)** After image processing.

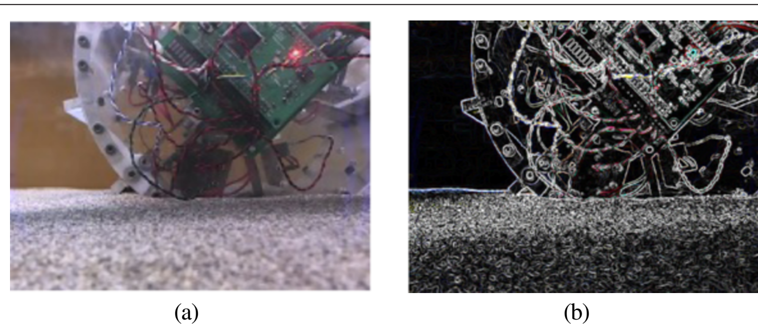

Figure 18 Contacting view between wheel with 15 kg load and loose soil. (a) Before image processing. **(b)** After image processing.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
KI took the lead in experimentation and wrote this paper as corresponding author. TS developed the sensing unit and carried out experiments. SS and TK supported experimentation. TK supervised presentation. All authors read and approved the final manuscript.

Acknowledgements
This work was supported by KAKENHI (23760223).

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Received: 17 March 2014 Accepted: 16 August 2014
Published online: 21 October 2014

References

1. Baugher JF (1987) The Spaceage Solar System. Wiley, New York
2. NASA (2012) Mars Pathfinder. http://www.nasa.gov/mission_pages/mars-pathfinder/. Accessed 25 Nov 2013
3. NASA/JPL (2012) Mar Exploration Rovers. http://mars.jpl.nasa.gov/mer/home/index.html. Accessed 11 Oct 2013
4. Bekker M (1956) Theory of Land Locomotion; the mechanics of vehicle mobility. The University of Michigan Press, Ann Arbor
5. Senatore C, Wulfmeier M, Jayakumar P, Maclennan J, Iagnemma K (2012) Investigation of Stress and Failure in Granular Soils for Lightweight Robotic Vehicle Applications. The Michigan Chapter of the National Defense Industrial Assocoation (NDIA), Proceedings of the Ground Vehicle Systems Engineering and Technology Symposium, MSTV session (1:30–2:00, THURSDAY, AUGUST 16)
6. Meirion-Griffith G, Spenko M (2011) A modified pressure–sinkage model for small, rigid wheels on deformable terrains. J Terrramech 48(2):149–155
7. Irani RA, Bauer RJ, Warkentin A (2011) A dynamic terramechanic model for small lightweight vehicles with rigid wheels and grousers operating in sandy soil. J Terrramech 48(4):307–318
8. Ding L, Nagatani K, Sato K, Mora A, Yoshida K, Gao H, Deng Z (2010) Terramechanics Based High-Fidelity Dynamics Simulation for Wheeled Mobile Robot on Deformable Rough Terrain. Proc. of the 2010 international conference on Robot and Automation, pp 4922–4927
9. Ding L, Deng Z, Gao H, Nagatani K, Yoshida K (2011) Planetary rovers' wheel-soil interaction mechanics: new challenges and applications for wheeled mobile robots. J Intell Serv Robot 4:17–38
10. Krebs A, Thueer T, Carrasco E, Siegwart R (2008) Towards Torque Control of the CRAB Rover. Proc. of International Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS): SESSON 5, m041-Krebs.pdf
11. Nagatani K, Ikeda A, Sato K, Yoshida K (2009) Accurate Estimation of Drawbar Pull of Wheeled Mobile Robots Traversing Sandy Terrain Using Built-in Force Sensor Array Wheel. IEEE/RSJ. Proceeding of International Conference on Intelligent Robots and Systems (IROS), pp 2373–2378
12. Sasaki T, Iizuka K, Suzukawa Y, Yamano M (2011) Development of Wheels with Tactile Sensors for Lunar Rovers. Proc. of The Robotics and Mechatronics Conference (in Japanese): 1A2-K11(CD-ROM)
13. Ishigami G, Nagatani K, Yoshida K (2006) Path Following Control with Slip Compensation on Loose Soil for Exploration Rover. Proc. of the 2006 IEEE/RSJ Int. Conf. on Robots and Systems (IROS), pp 5552–5557
14. Ding L, Gao HB, Deng Z, Nagatani K, Yoshida K (2011) Experimental study and analysis on driving wheels' performance for planetary exploration rovers moving in deformable soil. J Terrramech 48(1):27–45
15. Ding L, Gao H, Deng Z, Tao JG (2011) Wheel slip-sinkage and its prediction model of lunar rover. J Cent S Univ Technol 17(1):129–135
16. Sutoh M, Nagaoka K, Nagatani K, Yoshida K (2013) Design of wheels with grousers for planetary rovers traveling over loose soil. J Terrramech 5(5–6):345–353
17. Kyowa Electronic Instruments co., LTD (2013) http://www.kyowa-ei.us/eng/index.html. Accessed 11 Jun 2013
18. Iizuka K, Kubota T (2012) Study on effect of grousers mounted flexible wheel for mobile rovers. J Asian Electric Vehicles 10:1591–1597
19. NASA (2014) Jet Propulsion Laboratory, Rover speed. http://mars.nasa.gov/mer/mission/spacecraft_rover_wheels.html. Accessed 25 July 2014
20. Japanese Industrial Standards Committee (2014) https://www.jisc.go.jp/eng/index.html. Accessed 1 June 2014

doi:10.1186/s40648-014-0015-6
Cite this article as: Iizuka et al.: Study on grouser mechanism to directly detect sinkage of wheel during traversing loose soil for lunar exploration rovers. *ROBOMECH Journal* 2014 **1**:15.