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二輪小型月面探査機における起き上がりを生じさせる特殊車輪形状の評価

Evaluation of Special Wheel Designs for a Rebounding Mechanism in a Two-Wheeled Small Lunar Rover

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1. Introduction

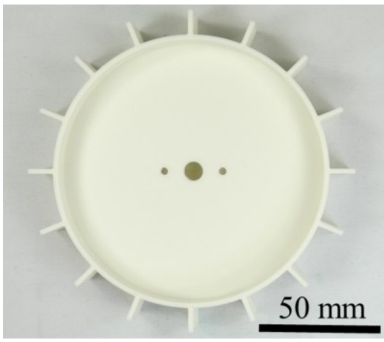
The discovery of water ice at the lunar south pole[1)] and the identification of lunar pits as potential habitation sites[2)] have accelerated plans for human presence on the Moon. Before sending humans to the Moon, exploration by rovers is necessary. These rovers primarily come in two sizes, large and small, each suited for different operational fields. For initial exploration and investigation of unexplored areas, small ones are more appropriate from the perspective of mission risk distribution. This is because small rovers have lower development and launch costs per unit, allowing multiple rovers to be launched simultaneously.

However, small rovers face challenges such as reduced mobility due to regolith and limited onboard energy capacity due to their size. Particularly on soft terrain like the lunar surface, the "stuck" phenomenon easily occurs, where wheels fail to gain sufficient reactive force from the ground, causing the rover to sink. Previous studies have reported that applying special wheel shapes can improve climbing performance[3-5)]. As experimental conditions differ across these studies, however, there is a need to compare different wheel shapes under unified conditions.

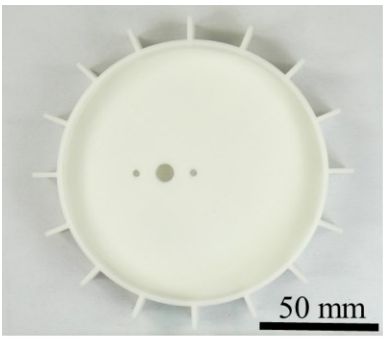
Therefore, this research compares multiple geometrically unique wheel shapes to identify the most suitable wheel design and its characteristics for a two-wheeled small lunar rover. The aim is to facilitate the operation of small rovers and accelerate lunar exploration.

2. Methods

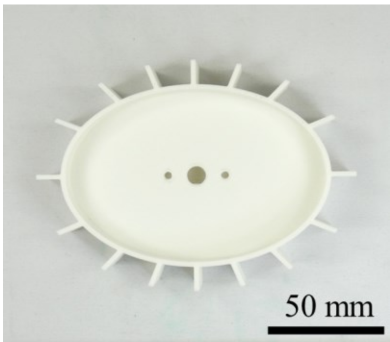
Figure 1 shows the six types of wheels used in this study (hereafter referred to as the Circular Wheel, Eccentric Wheel[3)], Elliptical Wheel[4)], Three-Blade Wheel, Triangular Wheel, and Square Wheel). The five types of wheels excluding the Circular Wheel are collectively called the special wheel group. The lugs are 10 mm long, and the maximum outer diameter of the wheels, excluding the lugs, is uniformly set at 110 mm. **Figure 2** shows an external view of the rover. The rover's dimensions are 135 mm in width, 130 mm in height, and 260 mm in depth. The mass is adjusted to 480 g by using additional weights, ensuring uniformity across all six cases.



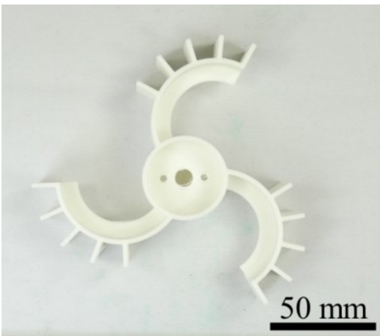
(a) The Circular Wheel



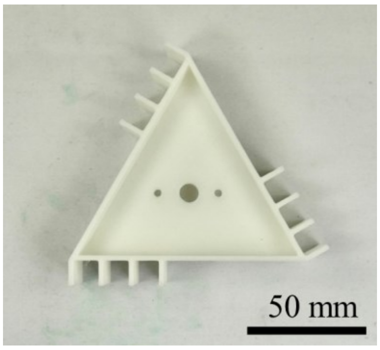
(b) The Eccentric Wheel



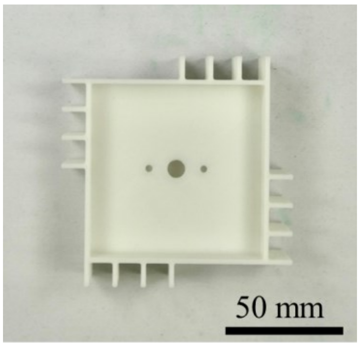
(c) The Elliptical Wheel



(d) The Three-Blade Wheel



(e) The Triangular Wheel



(f) The Square Wheel

Figure 1. Six types of wheels

Figure 3 presents a schematic diagram of the test course. The ground material consists of a 1:1 mixture of No. 5 and No. 6 silica sand (from Takeori). The travel distance is set at 300 mm, and for each wheel type, we evaluated the running time and power consumption required to traverse slopes ranging from 0° to 30° in 5° increments.

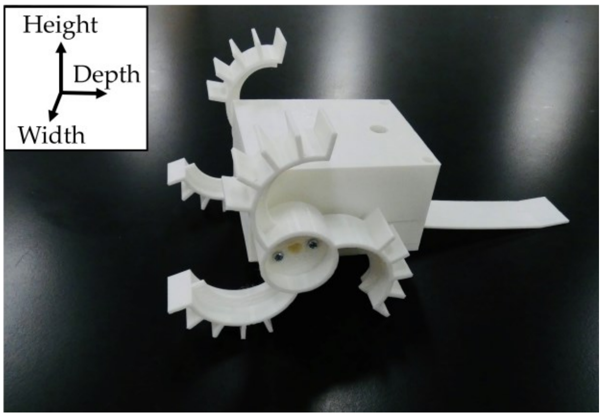


Figure 2. The external view of the rover

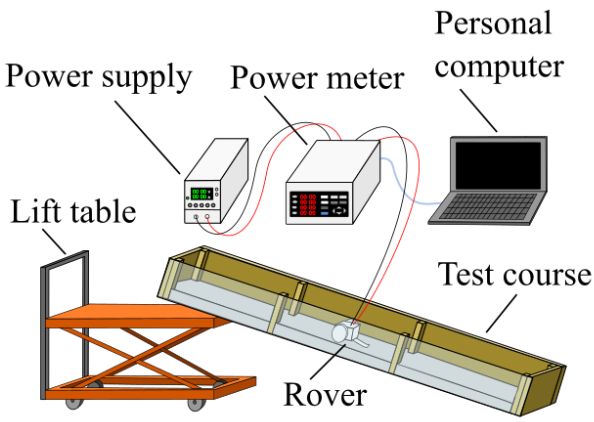


Figure 3. The schematic diagram of the test course

3. Results and Discussion

Figure 4 shows the results of the running time for the rover with each wheel type. The Circular Wheel was able to climb slopes up to 25°, but at 30°, it could not climb due to the "stuck" phenomenon. On the other hand, the special wheel group was able to climb slopes up to 30°. The running times for climbing the 30° slope, in order from shortest to longest, were: the Three-Blade Wheel 11.02 s, the Square Wheel 21.47 s, the Triangular Wheel 23.42 s, the Elliptical Wheel 24.05 s, and the Eccentric Wheel 33.43 s. Comparing the running times of the Circular Wheel and the Three-Blade Wheel on a 25° slope, the Circular Wheel took 42.16 s while the Three-Blade Wheel took 9.59 s. This means the Three-Blade Wheel is 77.3% faster than the Circular Wheel. Furthermore, comparing the power consumption under the same conditions, the Circular Wheel consumed 31.80 mWh, while the Three-Blade Wheel consumed 3.51 mWh. This indicates that the Three-Blade Wheel consumes 89.0% less power than the Circular Wheel.

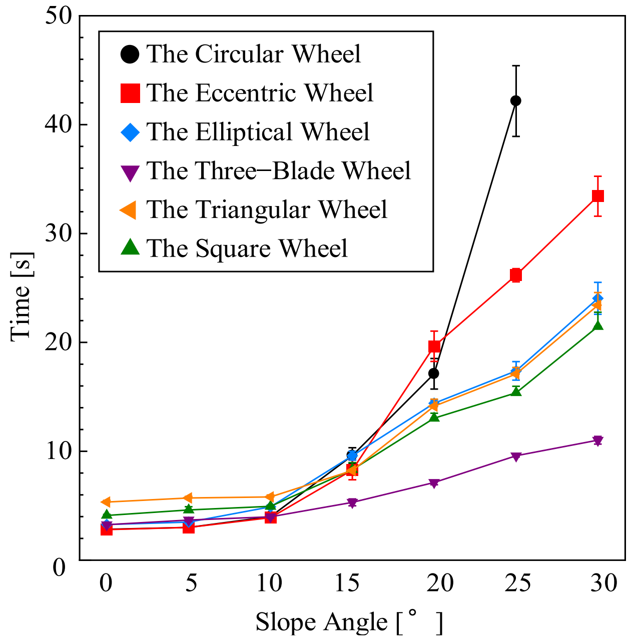
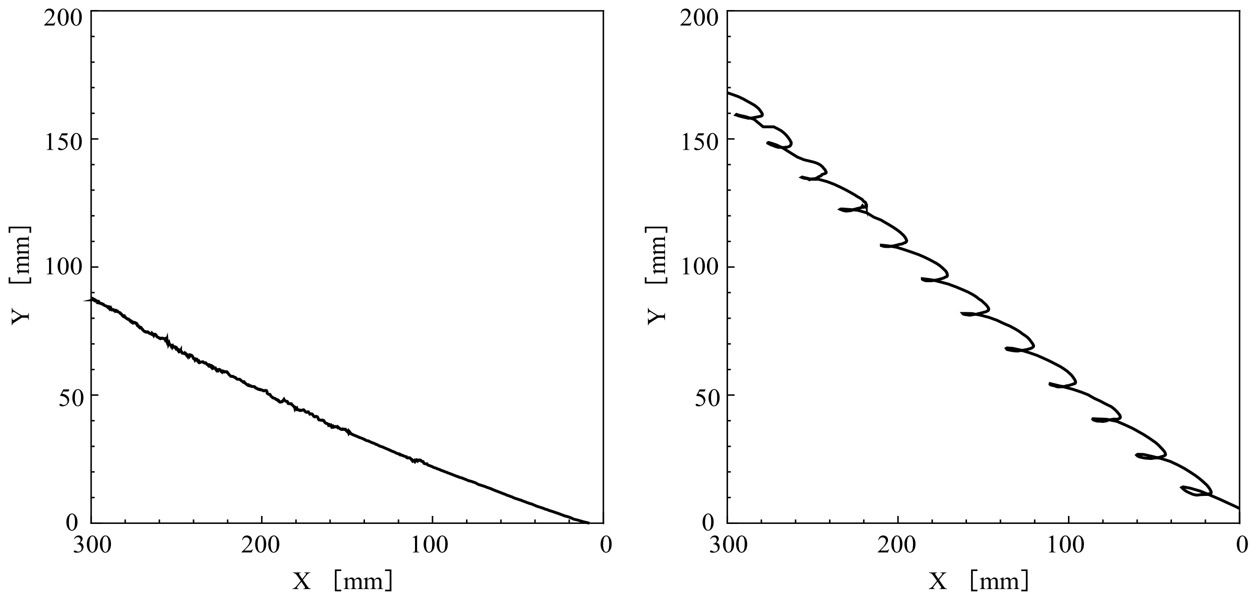


Figure 4. Running time

Figure 5 shows the travel trajectories of the rover using the Circular Wheel (at 25°) and the Three-Blade Wheel (at 30°). While the Circular Wheel doesn't cause vertical motion, the Three-Blade Wheel induces up-and-down movement. This vertical motion was observed in all special wheel types capable of climbing a 30° slope. Hereafter, we refer to this up-and-down motion of the rover as "rebounding", as it resembles the movement method of mudskippers. Mudskippers are fishes that inhabit tidal flats and move forward by lifting their bodies using their fins. The cause of the rover's rebounding is the change in distance between the shaft and the ground contact surface. **Figure 6** illustrates the rebounding of the rover when using the Three-Blade Wheel. The special wheel group travels while varying the distance between the shaft and the ground surface. The difference between the shortest and longest distances due to this characteristic causes the rebounding. This will most likely enable the rover to climb slopes up to 30° by lifting the body with the wheels and to escape from sinking.



(a) The Circular Wheel (25°)

(b) The Three-Blade Wheel (30°)

Figure 5. Travel trajectories[6)]

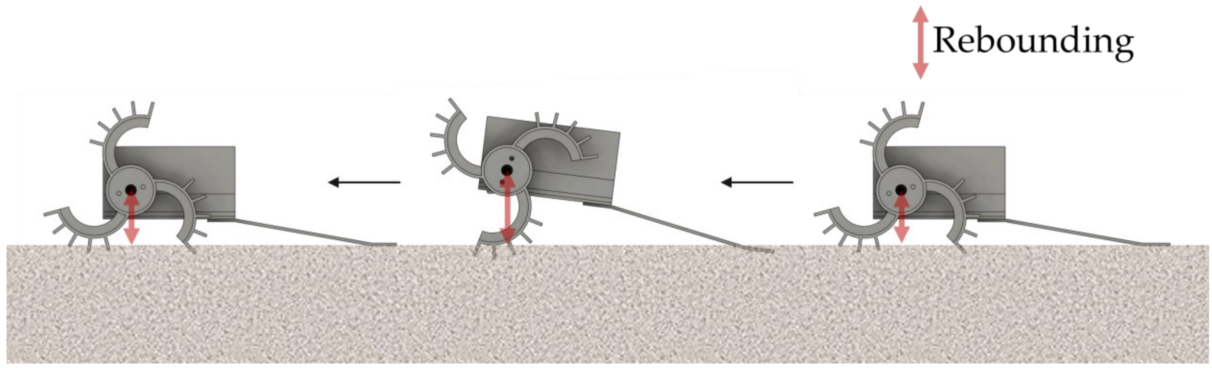


Figure 6. Rebounding of the rover with the Three-Blade Wheel

Table 1 shows the rebounding, the number of rebounding, and the total sum of rebounding for each special wheel type during a 30° slope climb. The rebounding refers to the vertical displacement of the rover in a single lift-up event. The number of rebounding is the count of rebounding that occur in one complete wheel rotation. The total sum of rebounding is the product of the rebounding and the number of rebounding, representing the total lift-up distance per wheel rotation. The order of wheels from highest to lowest total sum of rebounding matches the order from shortest to longest running time. Therefore, wheels with a greater total sum of rebounding improve the climbing performance of the two-wheeled small rover.

Table 1. The values of rebounding for each wheel (30°)

Wheel Type	Rebounding [mm]	The Number of Rebounding	Total Sum of Rebounding [mm]
The Circular Wheel	N/A	N/A	N/A
The Eccentric Wheel	16.68	1	16.68
The Elliptical Wheel	9.98	2	19.96
The Three-Blade Wheel	13.29	3	39.87
The Triangular Wheel	7.59	3	22.77
The Square Wheel	6.85	4	27.40

4. Conclusion

In this study, we compared the climbing performance of six types of wheels, including special wheels. As a result, we observed that the special wheel group, which was capable of climbing a 30° slope, caused the rover to rebound. This rebounding effect is due to changes in the distance between the shaft and the ground contact surface. Among the special wheel group, the Three-Blade Wheel demonstrated the most superior performance. Compared to the Circular Wheel, which is commonly used on hard terrain, the Three-Blade Wheel traversed the course 77.3% faster and consumed 89.0% less power. This is attributed to the greatest total sum of rebounding. For a two-wheeled small lunar rover, wheel shapes that produce a larger total sum of rebounding improve climbing performance.

References

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