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Empirical Study on Characteristics of Angled Spoke-Based Wheels on Granular Media

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ABSTRACT

In this study, the optimal shape of angled spoke-based wheels (ASWs) was designed to maximize the driving speed of a mobile robot with ASWs on granular media. As a lightweight search and rescue mobile robot, it is required to have a high driving speed to reach the disaster site quickly. When granular media behave as fluids, slippage occurs, and the mobile robot slows down compared with when the media behave similarly to a solid ground. There are no exact criteria to explain the behavior of granular media. Therefore, the Taguchi method and $L_9(3^4)$ orthogonal array were employed to empirically optimize the shape of the ASW. The design variables evaluated were the motor RPM, width–height proportion of the foot, radius of curvature, and toe angle of the foot. The size of the ocher balls was adopted as the user condition. An orthogonal array and signal-to-noise (S/N) ratio were used to analyze the validity of the design variables. The optimal design variables of the ASW were a motor RPM of 6000, width–height proportion of 3:7, radius of curvature of $1.0 \times h$, and toe angle of 15deg. Verification experiments were performed to evaluate the improved driving speed of the ASW. The angular velocity of the ASW increases by 2.79% for $\phi 1$ (mm) and 10.50% for $\phi 6$ (mm). Therefore, an optimized ASW design is expected to improve the driving speed of a mobile robot with ASWs.

Introduction

Numerous technologies have been developed for disaster prevention. However, unexpected disasters, such as Deepwater horizon oil spills, have occurred. When a maritime disaster occurs, it is difficult for a wheeled vehicle, large equipment, or human operators to reach the site. Furthermore, relief and search and rescue (SAR) should be performed within 72 hours, because it is a critical time to rescue human life¹. Small-sized mobile robots have the advantage of fast access to disaster sites and are capable of exploring blind spots.

For fast access to maritime disasters, a new approach to the maritime disaster site is suggested in Figure 1. To reach the site, the mobile robot with angled spoke-based wheels (ASWs) should pass through the sand surface. This makes it difficult for a wheeled vehicle to access the site. As shown in Figure 1-(a), when a ship is wrecked at sea, robots should pass the sand surface to approach the water. Figure 1-(b) illustrates the maritime rescue carried out on the shore. This requires robots to walk on the sand.

Figure 1. Application of the mobile robot with ASW. (a) Example of maritime SAR. A ship is wrecked on the ocean. (b) Example of maritime relief.

Sand is the most representative granular medium. Granular media refers to a collection of particles that behave solid- and liquid-like². Therefore, the locomotion of legged robots can be divided into two types, namely walking and swimming³. The motor RPM and the volume fraction of a granular medium determine the fluidization of the medium⁴. Walking locomotion occurs at a relatively low motor RPM and high volume fraction, whereas swimming locomotion occurs when the motor RPM increases and the volume fraction decreases⁵.

The shape of the ASW should be optimized empirically. There are theories to explain the characteristics of granular media; however, they are not well modeled. In addition, parameters affecting the driving abilities of robots vary with conditions such as low motor RPM⁶, high motor RPM⁷, overshoot of force⁸, and fluctuation of force⁹.

Research has been conducted to design the limbs of mobile robots to locomote on granular media. The most representative research is the study on RHex-class robots such as Sandbot, AmphiHex-I, AmphiHex-II, and a flipper-based robot called Fbot. RHex-class robots have vertically spinning one-degree-of-freedom curved-shaped legs. Studies on Sandbot^{4,10-12} focused on the direction and degree of curvature. In addition, prior studies also examined AmphiHex-I^{13,14} focused on the influence of the shape of its elliptical leg. These studies showed that the greater the curvature, the faster do the mobile robots advance. Another approach that shifts materials with different stiffness has been performed with AmphiHex-II³. A lower stiffness can result in a faster driving speed on granular media. Meanwhile, Fbot¹⁵ has legs with two degrees of freedom that push off the granular media horizontally. It was shown that legged robots can not only move on solid terrain but also locomote on granular media. However, although both types of walking methods are capable of locomotion on a granular surface, their speed is significantly low for SAR. RHex classed legs spin in a circle when granular media fluidized owing to high motor RPM. In addition,, Fbot advances only a short distance with a single swing.

The ASW mechanism was adopted in this study. ASW has advantages for disaster relief and SAR such as high driving speed, various surface drivability, and the ability to overcome obstacles. By changing the shape of the preceding ASW, the driving speed on granular media was increased. Precedent ASWs experienced a speed drop owing to the slippage on granular media¹⁶. It had a cylindrical shape for a single point contact with the ground. Although the penetration of spokes into granular media was high, the contact area was limited. Therefore, its driving speed drops owing to the slippage caused by the low drag force. To prevent slippage and increase the driving speed, a new design for ASW is required. A newly introduced design can adjust parameters that affect the driving speed of the ASW.

The remainder of this paper is organized as follows. Section 2 defines the problem of ASWs on granular media. Section 3 explains robust design planning, including the objective function, design variables, and user condition. Section 4 details the experimental results and discussion. Finally, conclusions are presented in Section 5.

Configuration of ASW

Problem definition

Granular media have a unique characteristic that they can exhibit solid- and fluid-like behavior². Granular media become fluidized when slippage occurs between the grains. The speed of ASW on granular media drops when granular media behave fluid-like. There are three main factors that decrease the driving speed of ASW: motor RPM⁴, volume fraction⁵, and grain mass¹⁷.

When the motor RPM is low, granular media behave similarly to a solid ground, whereas they behave fluid-like for higher motor RPMs⁴. When a legged robot locomotes on solidified granular media, limb kinematics determines the speed of the legged robot¹⁷. However, during swimming locomotion on fluidized granular media, slippage occurs and the speed drops⁶. The volume fraction ϕ is another main factor that determines the driving speed of the ASW. The volume fraction is defined by equation (1), which is the volume of granular media V_{solid} over the volume occupied $V_{occupied}$ ¹⁸,

$$\phi = V_{solid}/V_{occupied} \quad (1)$$

The drag force is influenced by the penetration depth and contact area¹⁷. Densely packed granular media with a high volume fraction prevent ASW from penetrating deeply. However, loosely packed granular media with a low volume fraction can allow the ASW to penetrate deeply. As the drag force of an ASW is influenced by the penetration depth and contact area¹⁷, the driving speed is dependent on the volume fraction. However, if the penetration is excessively high, the driving speed of the ASW can be decreased⁵. Therefore, an empirical study is necessary to ascertain the optimal conditions for the ASW.

The mass of the grain determines the critical force F_c to fluidize the granular media as shown in equation (2). If the applied force is higher than the critical force, slippage occurs. The critical force was calculated as follows¹⁷:

$$F_c = Agm_gj. \quad (2)$$

where A is a constant depending on the characteristics of granular media, g is gravity, m_g is the mass of a grain, and j is the depth of the penetration length of the ASW. The larger grain mass, the higher is the critical force. Therefore, advancing on granular media with heavy grains can result in less slippage.

Figure 2. Newly designed adaptive spoke wheel. It consists of a wheelbase, spoke, and foot. Six spokes and six feet are attached to one wheelbase.

Figure 3. 45 deg tilted work plane of newly designed ASW. ASW advance using thrust force generated when feet push off granular media.

Foot and Spoke configuration

To improve the driving speed, the newly introduced spoke design shown in Figure 2 consists of the following three parts: a wheelbase, spoke, and foot. The design variables of the foot configuration were determined to maximize the driving speed of the ASW. The design variables determine the contact area, the ability to penetrate granular media, and the thrust force of a foot. The design was optimized to maximize the driving velocity of the ASW on granular media.

The ASW has a unique workspace that is tilted at 45 deg. The newly designed model shown in Figure 3. follows the same mechanism. This tilted workspace changes the contact area of the ASW projected onto the XZ plane. The mobile robot with ASW advances along the Y axis, and this change affects the driving speed.

Experiment design

Taguchi method

The Taguchi method was used to demonstrate the robustness of the ASW^{19,20}. As the characteristics of granular media change with the motor RPM and volume fraction, an empirical study is required for the optimal design of ASWs. The Taguchi method was used to optimize the variables of the ASW with the least number of experiments^{21,22}. Three levels of the four design variables were used. The corresponding $L_9(3^3)$ Taguchi orthogonal array is used as shown in Table 4 and Table 5.

Objective and design variables

The purpose of this research was to maximize the driving speed of ASW on granular media. The driving speed was measured as the average angular velocity of the ASW using the root mean square (RMS) method. Design variables that influence the driving

Design Variables		Level 1	Level 2	Level 3
A	Motor RPM	1000	2000	3000
B	Width-Height Proportion	7:3	5:5	3:7
C	Radius of Curvature	$2.0 \times h$	$1.6 \times h$	$1.2 \times h$
D	Toe Angle	-45 deg	0 deg	45 deg

Table 1. Design variables and levels for 1st experiment.

Design Variables		Level 1	Level 2	Level 3
A	Motor RPM	3000	4000	5000
B	Width-Height Proportion	3:7	2:8	1:9
C	Radius of Curvature	$1.2 \times h$	$1.1 \times h$	$1.0 \times h$
D	Toe Angle	-15 deg	0 deg	15 deg

Table 2. Design variables and levels for 2nd experiment.

speed of the ASW are determined. Figure 4 shows four design variables, that is, motor velocity, width–height proportion, radius of curvature, and toe angle. The levels of each design variables for the first and second experiments are presented in Table 1 and Table 2. Based on the results of the sensitivity analysis from the first experiment, the levels of each design variable were adjusted.

The motor RPM determines the characteristics of granular media. The width–height proportion influences the penetration and drag forces. It is the proportion between the width and height h of the projected area of a foot. If the proportion of height is greater, it can penetrate better. If the height is larger than the width, the friction drag will be greater. The radius of curvature influences the contact time. A longer contact time causes a higher y axis reaction force and levitates ASW. Finally, the toe angle was considered because ASW has a 45 deg tilted work plane. The angle between the contact area and driving direction of the ASW was defined as the toe angle. The toe angle ψ generates a directional force.

User condition

The grain size was selected as the user condition. Grain size is an important factor that affects both the volume fraction and critical force. In addition, when the mobile robot with ASWs is relieved, the SAR grain size cannot be predetermined. This must advance regardless of the grain size. Therefore, two different sizes of the ocher balls in Table 3 were determined. The size is presented as the diameter of the grain with ϕ (mm). For variable control, a controlled grain volume is required. Therefore, ocher balls of two different sizes, as shown in Table 3, were selected.

Figure 4. Design variables are defined as motor RPM, width-height proportion of projected area, radius of curvature, and toe angle.

Grain Size (mm)	Density (g/cm ²)	Volume Fraction	Mass of a Grain (mg)
$\phi 1$	2.2	0.47	1.18
$\phi 6$	2.2	0.4	254.47

Table 3. Specification of user conditions

Number of Experiment	Design Variables				User Conditions						S/N Ratio (dB)
	A	B	C	D	Grain Size 1(mm)			Grain Size 6(mm)			
					RMS Angular Velocity γ (deg/s)						
1	1	1	1	1	10.72	15.46	10.58	29.64	31.65	33.40	23.83
2	1	2	2	2	35.64	35.18	35.86	48.20	47.40	47.88	32.12
3	1	3	3	3	69.01	68.73	69.35	72.75	73.08	73.25	37.02
4	2	1	2	3	31.02	31.66	32.13	44.48	43.11	44.48	31.20
5	2	2	3	1	27.67	28.25	30.93	52.35	57.72	54.81	31.15
6	2	3	1	2	63.07	62.18	60.84	93.20	88.57	97.15	37.26
7	3	1	3	2	60.06	58.87	60.07	122.89	124.08	127.19	37.63
8	3	2	1	3	74.58	74.58	67.74	84.34	79.36	77.31	37.59
9	3	3	2	1	49.50	47.97	51.28	71.35	72.73	76.75	35.28

Table 4. $L_9(3^4)$ Orthogonal array of 1st Experiment

Number of Experiment	Design Variables				User Conditions						S/N Ratio (dB)
	A	B	C	D	Grain Size 1(mm)			Grain Size 6(mm)			
					RMS Angular Velocity γ (deg/s)						
1	1	1	1	1	162.8	161.66	176.4	206.27	202.3	200.78	45.21
2	1	2	2	2	189.4	185.23	171.41	201.36	206.32	199.14	45.62
3	1	3	3	3	248.7	225.78	247.14	218.03	225.64	223.19	47.25
4	2	1	2	3	308.52	293.45	289.11	301.6	301.42	299.85	49.51
5	2	2	3	1	229.94	218.84	234.27	248.91	245.98	243.63	47.47
6	2	3	1	2	212.49	198.18	195.66	270.51	250.4	259.21	47.05
7	3	1	3	2	251.36	270.49	295.93	317.02	296.79	290.74	49.09
8	3	2	1	3	286.66	300	305.79	324.92	293.15	270.52	49.41
9	3	3	2	1	176.17	196.22	205.67	289.14	291.11	292.94	47.09

Table 5. $L_9(3^4)$ Orthogonal array of 2nd Experiment

Figure 5. Experiment test bench: (a) test bench design; (b) assembled test bench.

Sensor	Model	Resolution (pulse/rev)
Rotary Encoder	HE40B-6-1024-6-L	1024

Table 6. Specification of sensor

S/N ratio

To maximize the driving speed of the ASW, the mesh characteristic formula (3) was used.

$$S/N \text{ ratio} = -10 \log \left| \frac{\left(\frac{1}{y_1}\right)^2 + \left(\frac{1}{y_2}\right)^2 + \dots + \left(\frac{1}{y_n}\right)^2}{n} \right| \quad (3)$$

where $y_i (i = 1, 2, \dots, n)$ denotes the measured RMS velocity of ASW and n represents the repetitions of an experiment under both user conditions.

Test bench

A test bench for the experiments is shown in Figure 5. The test bench consists of three units, namely a stationary unit, measuring unit, and mobile unit. The stationary unit consists of a frame of the test bench and a circular rail. The circular rail is filled with ocher balls, and the mobile unit moves along the rail.

The mobile unit consists of a ECX TORQUE 22L motor, one set of ASWs, and a squeeze. The motor RPM is controlled by EPOS2 24/5 controller. The mobile robot with ASWs for relief and SAR has a light weight. Its weight is approximately 1.2 kg. The payload on one set of ASW is approximately 300 g. Therefore, the payload of the ASW was set to 300g. As in the previous ASW, the spokes and feet are connected to a motor at 45deg angle. As the motor rotates, the foot in contact with the ocher ball propels, and the mobile unit advances along with the rail. The squeeze was connected to the opposite side of the motor. After the ASW walks on the ocher ball, it is left on the ocher ball. The squeeze flattens the surface of the ocher ball to initialize the surface conditions for the next revolution.

The measuring unit consists of an encoder and a rod, and they are placed so as to have the same concentricity with the rail. The length of the moment arm and the length between the center of the test bench and the motor is fixed at 250 (mm). The rod was connected to the HE40B-6-1024-6-L-5 encoder which is shown in Table 6, squeeze, and motor. The rod was fixed with an encoder with a shaft so that the encoder measures the angle of the rod. The squeeze was fixed with the rod. However, the motor is connected to the rod with two ball bushes, which creates degrees of freedom along the Z-axis. The angular velocity can be calculated on the basis of the measured angle.

Figure 6. Result of sensitivity analysis of 1st and 2nd experiments.

Experiment and result

Experimental method

The experiments were conducted with five revolutions. The assigned motor RPM, which makes the ASW spin, was applied. The ASW generates advancing movements and rotates along with a rod connected to a rotary encoder at the center of the test bench. The angle data of the rod was measured using an encoder, and the angular velocity was calculated based on the angle data. Please refer to the Multimedia extension for the experimental set-up and results. A total of five revolutions were conducted, and data from the second to fourth revolutions were used. The driving speed was calculated with the average angular velocity using RMS. In addition, the S/N ratios were calculated using equation (3).

Experimental result

The experiments were performed twice. The levels of design variables for the second experiment were determined from the results of the first experiment shown in Table 4. Based on the sensitivity analysis in Figure 6, the redirect scopes of levels are higher for motor RPM, width–height proportion, and radius of curvature. The scope of the toe angle is narrowed down the range because it has a maximum S/N ratio at level 2.

As Figure 6 illustrates, a high motor RPM is more sensitive in determining the fast driving speed of the ASW. The speed drop caused by fluidization did not affect the results of both experiments. Moreover, from the results in Table 4 and Table 5, it was found that the critical force is more dominant than the volume fraction to determine slippage on the ocher balls. The ASW showed a faster driving speed at $\phi 6$ (mm) than at $\phi 1$ (mm) although the volume fraction of $\phi 1$ (mm) is larger. This is because the mass of $\phi 6$ (mm) grain is greater than that of $\phi 1$ (mm) grain. $\phi 6$ (mm) granular media are 254.47 (mg) per grain and $\phi 1$ (mm) are 1.18 (mg) per grain. The experimental conditions under the two different user conditions were the same. Therefore, the mass of a grain dominated the slippage between grains.

From the sensitivity analysis of the first experiment shown in Figure 6, it was found that the driving speed of the ASW increases as the height proportion increases. Therefore, the second experiment was conducted using design variables with a higher length proportion. The results show that the width and length proportion of the projected area with a 3:7 proportion shows the greatest driving speed. With the same width of feet, as the proportion of width decreases, the penetrating area of the foot decreases. A smaller penetrating area creates a higher pressure to penetrate the granular media. Therefore, a smaller proportion of the width has a higher driving speed in the first experiment. However, in the second experiment, if the proportion of width was too small, the projected area of the penetrated leg decreased. This result shows a decrease in the driving speed.

From the first and second experiments, the curvature showed an increasing sensitivity, while the radius R increased. However, owing to the physical limit, R should be equal to or greater than the height h as shown in Figure 4. Therefore, the optimal value of R to make the curvature is when R is equal to h .

Figure 7. Result of validity experiments: (a) result of 1st validity experiment; (b) result of 2nd validity experiment.

Design Variables		Optimal Value
A	Motor RPM	5000
B	Width-Height Proportion	3:7
C	Radius of Curvature	1.0
D	Toe Angle	15

Table 7. Optimal value of ASW.

The optimal toe angle was 0deg in the first experiment. Therefore, the range of the toe angle was narrowed down, and the second experiment was conducted near 0deg. The second experiment showed that 15 deg had the highest sensitivity. This is because ASW has 45 deg tilted area, and it changes the projected contact area through the path of the foot.

Verification experiment

Verification experiments were conducted. The optimal foot features of the design variable combination of both experiments are shown in Table 7. The validation experiments were conducted under the same conditions. Average angular velocities were used to compare the optimal and orthogonal array experiments. The results are presented in Figure 7. The optimal design showed a speed improvement of 2.79 % and 10.50% on other balls of $\phi 1$ (mm) and $\phi 6$ (mm), respectively, compared to the fastest result of the orthogonal array.

Conclusion

In this study, the shape of the ASW was optimized. The design variables used in this study were the motor RPM, width and height proportion of the projected area of the foot, radius of curvature, and toe angle. The Taguchi method was used and based on the S/N ratio from $L_9(3^4)$, orthogonal array sensitivity analysis was conducted. Through sensitivity analysis, it was confirmed that the design variables are sensitive to the driving speed of ASW on granular media.

The optimal conditions for a higher driving speed of ASW on granular media were achieved through two experiments, as follows: the motor RPM was 6000, width–height proportion was 3:7, radius of curvature was 1.0×h, and toe angle was 15deg. Optimized ASW showed angular velocity of 305.78 (deg/s) on $\phi 1$ (mm) other ball, and 333.19 (deg/s) on 6 (mm) other ball. The optimal ASW showed a speed improvement of 2.79% and 10.50% on other balls of $\phi 1$ (mm) and $\phi 6$ (mm), respectively, compared to the fastest combination of orthogonal arrays.

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Author contributions statement

T.S., K.L. conceived the experiments, K.L., S.A., K.Y.Y and D.Y. conducted the experiments, K.L. and S.A. analysed the results, T.S. supervised the experiments, T.S. acquired funding. All authors reviewed the manuscript.

Supplementary Files

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