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Robust Design of a Screw-Based Crawling Robot on a Granular Surface

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ABSTRACT In this paper, a robust design of a screw wheel is presented, based on the Taguchi method to accelerate a screw-based crawling robot. Screw-based crawling robots have been studied before, but their application is limited because of their limited speed. To solve this problem, robust design is applied for the screw wheel geometry driving on granular surfaces, such as desert sand, which has not been studied before. Each of the four parameters determining the screw wheel geometry and two user conditions were set at three levels, and the Taguchi method was applied through the $L_9(3^4)$ orthogonal array. The experimentally optimized parameters were as follows: the slope angle was 35°, the height of the blade was 14 mm, the number of spirals was one, and the blade had a semicircular cross-section. A verification experiment was conducted with the optimized model to verify the Taguchi method's validity. In conclusion, the robust design using the Taguchi method is suitable for solving the speed problem of a screw-based crawling robot on a granular surface.

INDEX TERMS Screw wheel, robust design, Taguchi method, screw-based crawling robot, speed improvement.

I. INTRODUCTION

Screw-based crawling robots have received significant attention in the past as driving robots on rough terrains, which is difficult to drive with general circular wheels including granular terrains [1]–[3]. Screw-based crawling robots generally have two cylinders with blades attached to screws. Two screw wheels paired parallelly on an axis rotate in opposite directions to help the robot move forward. A strong tractive force can be developed based on the blade of the screw wheel and a large contact area with the ground. A strong tractive force allows the screw-based crawling robot to work better than a general circular wheel on a granular surface [4], [5]. Based on these advantages, screw-based crawling robots for driving on rough terrains, such as a granular terrain, have been studied [2], [5]. Despite such studies, the critical disadvantage of screw-based crawling robots in being slow is shown. This point led to conclusion that it was not good for practical use and a lower research attention.

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Solving the speed problem of screw-based crawling robots is necessary to solve the problem of interest in screw-based crawling robots, which has been reduced to speed problem, and the difficulty to utilize in practice. Reported studies were aimed at solving the speed problem using control methods or by analyzing the dynamics of the screw-based crawling robot itself [6], [7]. However, there were no studies on compensating for the speed shortcomings by optimizing the screw wheel's shape. Several prior studies have been conducted on screw geometry, but it has been about drilling performance and when moving in the ground. It was different from the content about the speed of screw-based crawling robots driving on the granular surface [8], [9]. Therefore, for the robust design of a screw-based crawling robot, parameters for screw wheels are established. Optimization via the Taguchi method is applied to these parameters. The Taguchi method is very efficient as an optimization tool when the optimal conditions can be obtained through minimal experimentation [9]. It is suitable for use in scenarios with an incomplete mechanical interpretation because it is based on statistics rather than modeling [9], [10]. The dynamic analysis of screw-based crawling robots' movement on a granular surface remains incomplete. The relationship between a wheel's rotation and a granular surface depends on the wheel's rpm [9], [11]. When the wheel rotates at low rpms, the surface has a general characteristic, and when it rotates at high rpms, the surface has a fluid characteristic [12]–[20]. Changes in surface features make accurate mechanical predictions between the screw wheel and granular surface difficult. The problem of a screw-based crawling robot driving on granular surfaces is an appropriate scenario for applying optimization techniques based on the Taguchi method.

In this study, a robust design using the Taguchi method was applied to a screw wheel to increase the screw-based crawling robot's speed. The speed data of the screw-based crawling robot are obtained through experiments on the test bench. In terms of design parameters, four types of wheel geometries are expected to affect speed, each of which has three levels. The objective function is set as the forward speed per revolution (mm/rev). The main motivation behind this study is that optimization techniques using the Taguchi method can effectively improve the speed of screw-based crawling robots on a granular surface.

The paper is organized as follows. The experimental robot's prototype and a simple mechanical driving principle are described in Section 2. Section 3 describes the experimental setup for applying the Taguchi method. The experimental results and analysis are presented in Section 4. Finally, the significance and conclusions of this study are presented in Section 5.

II. THE PROTOTYPE OF THE SCREW-BASED CRAWLING ROBOT

In this section, a prototype of the screw-based crawling robot is described. This prototype borrows the form of a robot studied by Osíski and Szykiedans [2] from several previously studied types of screw-based crawling robots.

A. PROTOTYPE OF SCREW-BASED CRAWLING ROBOT

The model of the screw-based crawling robot used in the experiment is shown in Fig. 1. The dimensions of the screw-based crawling robot are 165.28 mm, 217.72 mm, and 80.94 mm (except for the wheel's blade, laser sensor reflector, and weight basket). The screw wheel is powered by two geared motors with an encoder. A DC motor (IG32GM+ENCODER 05TYPE (12V), D&J WITH Co., Ltd.) is used, and its specifications are shown in Table 1. Power without any problem with driving is supplied through the power-supply. For convenience, the screw wheels can be easily attached and detached in the experiment.

B. DRIVING PRINCIPLES OF SCREW-BASED CRAWLING ROBOT

As the screw wheel rotates, the force between the granular particles on the ground and screw wheel's blade is shown in Fig. 2. There are two forces between the particle and blade: normal force and tangent force. The normal force is the dominant one [2], [4]. The robot moves forward with a pair of screw wheels rotating in opposite directions. The forces between the two screw wheels are illustrated in Fig. 3. The robot's forward force F_v and the horizontal force F_h come from the dominant force, F_n. The horizontal forces eliminate each other, leaving only the forward forces, which helps them move forward [2], [4]. Using this principle, the robot can move forward, backward, or left/right, depending on the direction of the screw wheels' rotation.

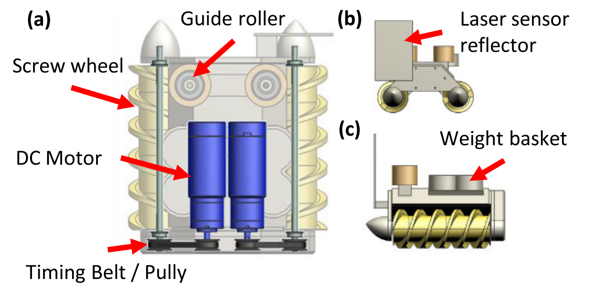

FIGURE 1. Modeling of a screw-based crawling robot.

TABLE 1. Geared dc motor specification.

Specification	Quantity	Unit
Geared ratio	1/19	-
Geared rated torque	2.3	(kgf-cm)
Rated torque	240	(gf-cm)
Rated current	750	(mA)
No load current	130	(mA)
Rated output	12.7	(W)

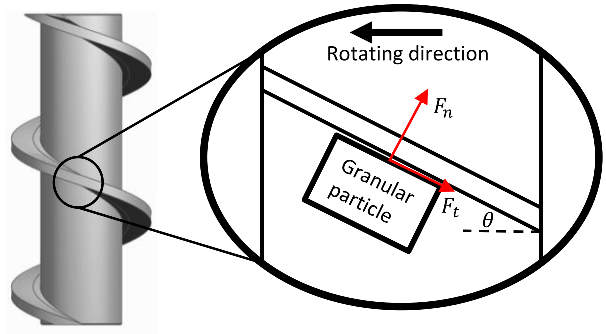

FIGURE 2. Forces between the blade of the wheel and the ground particle on the granular surface (F_n: normal force, F_t: tangent force, θ: angle of blade).

III. EXPERIMENTAL SETUP

A $L_9(3^4)$ orthogonal array based on four parameters- and two user conditions was designed for using the Taguchi method [21]–[23]. These robust design parameters are based on the experimental results and corresponding S/N ratios. Selected parameter values are used for verification experiments.

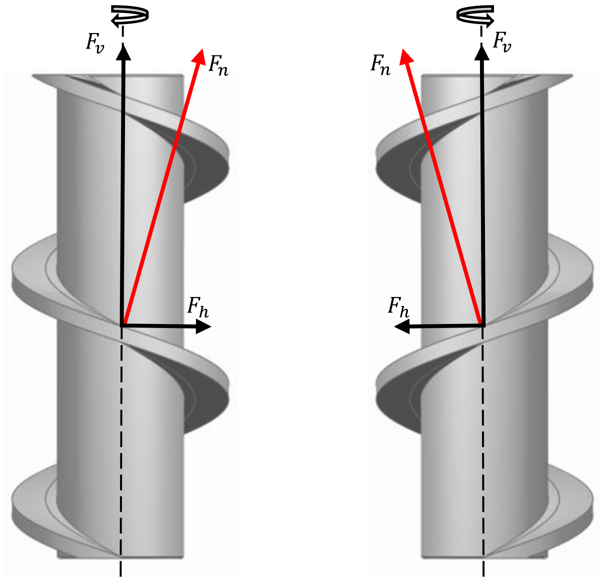

FIGURE 3. Forces of two screw wheels rotating in opposite directions (F_n: normal force, F_v: vertical force, F_h: horizontal force. The relation equation between them is as follows: $F_v = F_n \times cos\theta$, $F_h = F_n \times sin\theta$ (θ is from Fig.2)).

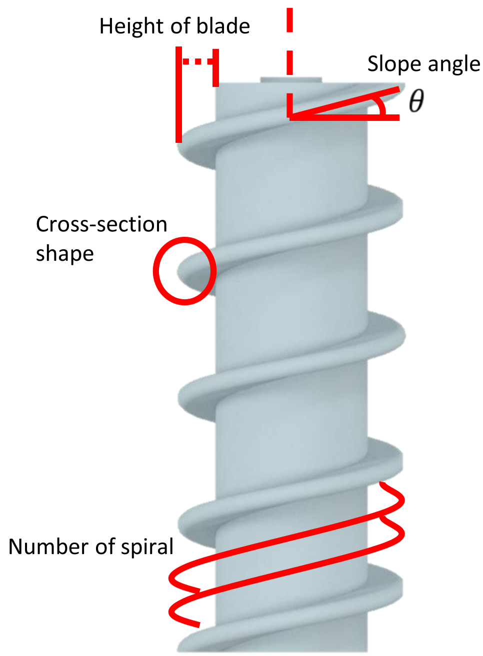

FIGURE 5. Design parameters of screw wheel.

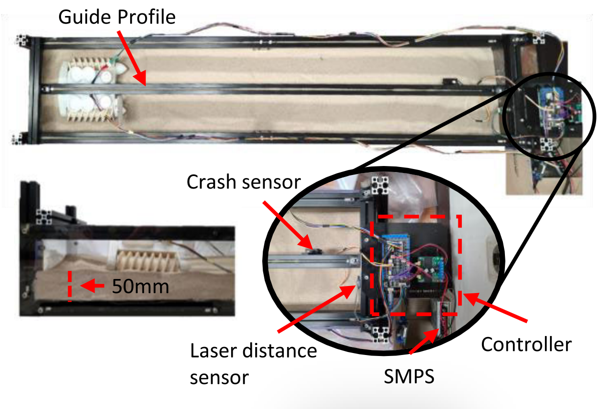

FIGURE 4. Structure of test bench.

TABLE 2. Laser sensor specifications.

Specification	Quantity	Unit
Emitter	940 nm laser	-
Max distance	400	(cm)
Max ranging frequency	50	(Hz)

A. THE EXPERIMENT TEST BENCH

The experiment was conducted on a test bench measuring $1.56m \times 0.3m \times 0.3m$. The size of the test bench considered the size of robot, to avoid interfering with the test's progress. The structure of the test bench is shown in Fig. 4. In the controller part, the motor is controlled through a motor drive. A dual VNH3SP30 motor driver carrier MD03A was used as the motor drive. Guide profiles were used to compensate for the 1-axis straight-forward motion of the robot. An OSTSen-VL53L1X sensor was used for speed measurement, and its specifications are listed in Table 2. The laser sensor reflector shown in Fig. 1 was used along with the laser sensor to receive real-time speed data. To emulate a granular surface, sand was piled up approximately 50 mm from the bottom of the test bench. The sand was composed of river sand from the Nakdong River, which is available in the market. This sand is classified as dry sand, with a size of 0.2mm-0.7mm, similar to 0.1mm-1mm for granular particles such as desert sand [24]. In each experiment, the same starting conditions were ensured by flattening the sand prior to the start of the velocity measurement.

B. TAGUCHI METHOD DESIGN

The Taguchi method is based on statistical methods as a tool for optimization. It is used to obtain optimal conditions through minimal experiments and is already being widely used in the field of optimization [21].

1) DESIGN PARAMETER AND USER CONDITIONS

To use the Taguchi method, the design parameters and their corresponding levels must be set. In this experiment, four parameters of the screw wheel are selected, as shown in Fig. 5. They are the slope angle, height of the blade, number of spirals, and cross-section shape of the blade. Each parameter is divided into three levels. The values for each level are listed in Table 3. The slope angles differ by 5° from the 30° used in the models of Osí ski and Szykiedans [2]. Based on the

TABLE 3. Screw wheel's design parameters.

	Design Parameter	Level 1	Level 2	Level 3
A	Slope angle (°)	25	30	35
B	Height of blade (mm)	6	10	14
C	Number of spirals (-)	1	2	3
D	Cross-section shape	◓	■	▲

TABLE 4. User conditions of screw wheel.

	User condition	Level 1	Level 2	Level 3
A	Load (g)	0	500	1000
B	Motor rpm (rev/min)	250	300	350

blade height of 10 mm, we selected 6 mm at the same interval as 14 mm, which is the maximum structure of the robot. The number of spirals and cross-section shapes are shown in Table 3.

Table 4 lists the user conditions. The load on the screw-based crawling robot and the motor rpm are set as user variables. Each condition is set at three levels. The load on the screw-based crawling robot was selected as a user condition because it depends on the robot's utilization. The values corresponding to each level are no load, 0.5× the weight of the robot (500 g), and 1× the weight of the robot (1,000 g). The load was applied through the weight. As for the rpm, a smooth operation interval of the robot was measured through the first experiment. Based on this, the level was determined through a difference of 50 rpm at approximately 300 rpm.

2) ORTHOGONAL ARRAY DESIGN

Table 5 shows the orthogonal array of $L_9(3^4)$ for the four design parameters (A: slope angle, B: height of blade, C: number of spirals, and D: cross-section shape) and two user conditions (A: load, B: motor rpm). Forward distance per revolution was set as the objective function. The speed was measured experimentally, and the objective function value was obtained by dividing the measured speed with the motor rpm. Fig. 6 shows a real model based on the corresponding figures for each parameter.

3) APPLICATION OF TAGUCHI METHOD

The Taguchi method uses signal-to-noise (S/N) ratio to determine the optimal design parameters. Depending on their purpose, there are three methods of analysis: "lower-the-better," "higher-the-better," and "nominal-the-better." Among these, the value of "when the robot is the fastest" is needed;

FIGURE 6. Design No. 1–9: real modeling of screw wheel.

therefore, we use the "higher-the-better" analysis method. Since the goal of the experiment was to obtain the robot's maximum speed, we used Equation (1) as follows.

$$S/Nratio = -10log\left|\frac{\left(\frac{1}{y_1}\right)^2+\left(\frac{1}{y_2}\right)^2+\cdots\left(\frac{1}{y_n}\right)^2}{n}\right|[dB] \quad (1)$$

where the y_i value is based on the experimental measurements, which is the forward distance per revolution (mm/rev), and i represents the i-th repeated experiment. n represents the total number of experiments.

IV. RESULT OF EXPERIMENT

The results of the experiment are presented in Table 5. The speed data were measured using the laser reflector, as shown in Fig. 1, and the laser sensor is shown in Fig. 4. Data at the beginning and the end were excluded to obtain stable speed measurement data. The forward distance per revolution was calculated by dividing the measured speed by the rpm value. The experiments were repeated three times to improve their reliability. Based on these values, the S/N ratio was calculated using Equation (1).

TABLE 5. $L_9(3^4)$ **Taguchi orthogonal array.**

Number of exp	Design parameters A Level	B Level	C Level	D Level	Forward distance per revolution (mm/rev) — User condition: Load (g) ($N_1 = 0, N_2 = 500, N_3 = 1,000$), Motor rpm (rpm) ($M_1 = 250, M_2 = 300, M_3 = 350$) $N_1 * M_1$	$N_1 * M_2$	$N_1 * M_3$	$N_2 * M_1$	$N_2 * M_2$	$N_2 * M_3$	$N_3 * M_1$	$N_3 * M_2$	$N_3 * M_3$	S/N ratio (dB)
					33.75	33.02	30.47	33.86	24.78	27.48	29.32	27.18	23.81	
1	1	1	1	1	31.46	28.46	27.51	31.72	25.99	29.19	27.3	26.75	22.86	**28.9244**
					32.45	29.23	28.82	31.16	25.89	26.44	28.54	27.25	22.99	
					9.215	8.64	6.848	6.797	9.717	6.486	6.585	5.515	6.499	
2	1	2	2	2	10.31	7.47	6.858	6.294	9.047	6.514	6.435	5.389	6.316	**16.6375**
					9.031	7.621	6.559	6.027	11.38	5.667	6.083	4.963	6.525	
					8.479	9.722	9.545	7.747	7.757	8.79	6.883	7.922	8.417	
3	1	3	3	3	9.309	8.614	8.545	7.512	7.469	7.709	6.778	7.662	8.498	**17.9907**
					8.934	8.495	9.144	6.583	7.361	8.685	7.041	6.64	7.865	
					10.357	10.93	10.573	8.654	7.008	9.622	5.936	6.452	4.215	
4	2	1	2	3	11.813	9.96	10.172	8.923	8.898	9.125	5.821	6.274	4.512	**17.1926**
					10.747	11.18	9.784	8.722	9.23	9.334	6.003	6.301	4.43	
					11.02	10.94	9.459	7.912	8.874	7.254	7.74	6.135	8.186	
5	2	2	3	1	9.751	11.14	9.955	6.863	9.442	7.268	6.678	6.697	8.14	**10.1199**
					10.37	10.82	10.69	8.673	9.252	8.31	6.445	6.085	7.932	
					54.97	53.23	58.39	53.72	57.55	60.76	57.89	58.6	56.32	
6	2	3	1	2	53.14	54.17	59.77	55.39	56.02	58.49	55.57	53.85	56.51	**34.8977**
					50.145	53.54	59.92	51.47	55.86	57.94	51.27	55.75	55.6	
					1.2828	1.9701	1.9842	1.7901	1.7829	2.1486	3.99	1.647	1.8846	
7	3	1	3	2	1.3554	1.0686	1.4004	0.9261	1.4856	1.7142	2.9931	1.2933	1.578	**3.44379**
					1.0713	1.7208	1.4949	1.7553	1.5042	1.4283	2.3955	1.1292	1.2219	
					51.01	53.32	54.72	49.88	55.75	49.83	42.39	43.86	44.43	
8	3	2	1	3	52.51	52.55	54.59	50.12	53.64	50.21	43.05	42.27	42.2	**33.7313**
					51.06	53.01	54.31	49.96	54	49.97	41.78	44.67	44.92	
					64.53	64.05	52.99	58.34	59.69	66.79	63.46	62	63.19	
9	3	3	2	1	64.37	63.88	51.28	59.11	52	67.15	64.63	61.6	61.03	**35.6589**
					65.12	63.66	52.46	58.87	56.73	68.1	64.932	61.376	62.11	

4) S/N RATIO ANALYSIS

Fig. 7 shows the S/N ratio for the design parameters. The most sensitive parameter was the number of spirals, which tended to decrease as the number of spirals increased. The larger the number of spirals, the smaller the number of granular particles between the blades. Owing to the small number of particles, the screw wheel cannot be supported well and easily slips, which is thought to degrade performance. The parameter with the next highest sensitivity was the height of the blade. The height of the blade increased with an increase in the S/N ratio, and an optimal value was observed at the structural limit of 14 mm. The higher the height of the blade, the larger the area of the blade penetrating the granular surface. This reduces the stress from pushing granular particles, thereby reducing the slip on sand. The slope angle showed a low sensitivity. This is because the forward distance of the screw wheel per revolution is defined as the lead, and the larger the slope angle, the larger the lead. However, slips in the horizontal direction decrease the forward distance of the screw wheel as the horizontal force and the lead increase simultaneously. Therefore, the increase in distance caused by the increase in leads below 35° is more influential than the decrease caused by horizontal slip, which increases to the right. Further experiments were

TABLE 6. Verification experiment results.

Number of exp	Design parameters				Forward distance per revolution (mm/rev)									S/N ratio (dB)
					User conditions Load (g) ($N_1 = 0, N_2 = 500, N_3 = 1,000$) Motor rpm (rev/min) ($M_1 = 250, M_2 = 300, M_3 = 350$)									
	A	B	C	D										
	Level	Level	Level	Level	$N_{1*}M_1$	$N_{1*}M_2$	$N_{1*}M_3$	$N_{2*}M_1$	$N_{2*}M_2$	$N_{2*}M_3$	$N_{3*}M_1$	$N_{3*}M_2$	$N_{3*}M_3$	
					75.17	72.03	68.18	71.81	64.22	69.32	61.07	58.05	61.29	
Optimal	3	3	1	1	69.03	69.27	72.6	69.17	64.79	65.42	61.7	55.21	60.85	**36.266**
					71.32	70.23	69.77	67.07	64.47	66.84	60.18	55.27	60.43	

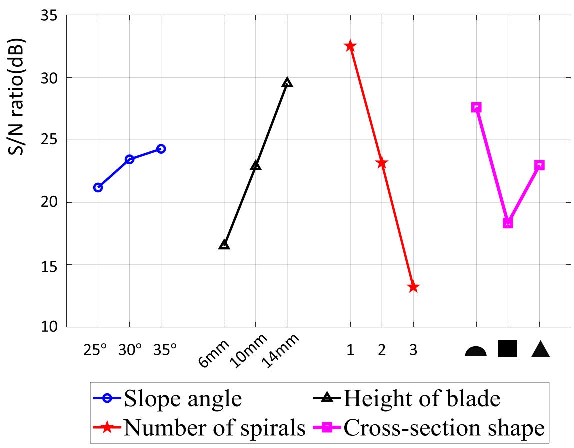

FIGURE 7. S/N ratio of design parameters.

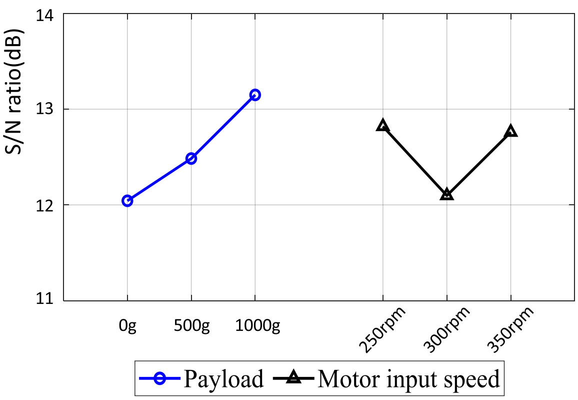

FIGURE 8. S/N ratio of user conditions.

deemed unnecessary as the upward trend reached a saturation point near 35°. The cross-section showed interesting results; the best performances were in the semicircular sections.

The S/N ratio value for the user condition is shown in Fig. 8. The load showed a low sensitivity but tended to increase. This is similar to the case of the blade. It was determined that the higher the load, the higher the area of penetration in the granular surface, and the higher the forward distance. The motor rpm also showed a very low sensitivity. Table 5 and Fig. 8 show that the tendency of motor rpm depends on the shape of the screw wheels under a small S/N ratio sensitivity.

5) OPTIMAL PARAMETER VALUE

The optimal design parameter values selected by the S/N ratio analysis corresponded to 3, 3, 1, and 1 levels. The slope angle was 35°, the height of the blade was 14 mm, the number of spirals was one, and the cross-section was semicircular. This newly manufactured model was not used in the previous experiment. A verification experiment conducted using an optimal model demonstrated an improvement. The results are presented in Table 6. This robustly designed model with optimal values was faster than the existing models in Table 5, except for the section with a load of 1,000 g for all user conditions. The S/N ratio of the robustly designed model is 36.266, which is higher than that of the existing models in Table 5. The S/N ratio comparisons demonstrate the model's improved performance.

V. DISCUSSION AND FUTURE WORK

The screw-based crawling robot moves forward through the force between screw-wheel and granular particle. When driving, the robot is disturbed by the particles in front of it, so it needs the power to overcome it and move on. The objective function 'Forward distance per revolution' is proportional to the pitch of the blade assuming that there is no disturbance when driving. The design parameter, Slope angle, means pitch in a situation where the length of the screw-wheel is fixed. In other words, the slope angle and speed are proportional. However, as mentioned earlier, the force to move forward is also an important factor because particles are interrupted when driving. These forces are eventually determined by the contact area between the screw-wheel blades and the granular particle and flow rate between the screw-wheel blades [8]. There are some differences from other similar experiments. The difference in experimental factors was that the degree of burying particles when moving was different, so the relation ship between contact area and the flow rate was different. For this work, it is treated in Future work paragraph. In real experiments, the degree of buried screw-wheel blades

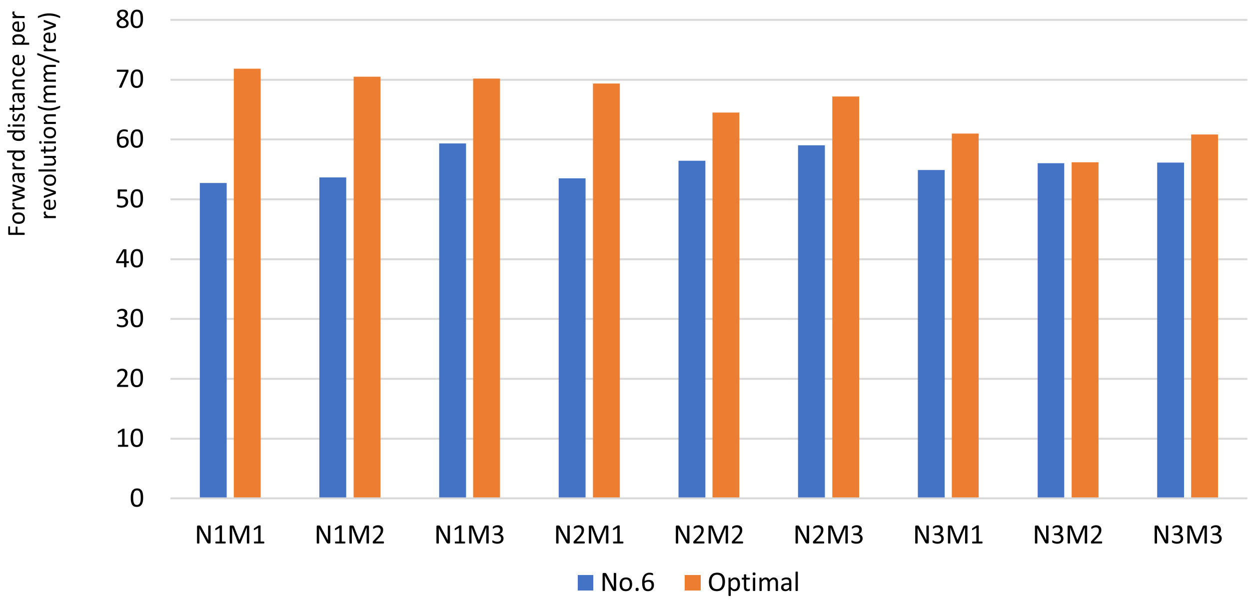

FIGURE 9. Comparison of forward distance per revolution between No. 6 and optimized design (User condition: Load (g) (N1 = 0, N2 = 500, N3 = 1,000); Motor rpm (rev/min) (M1 = 250, M2 = 300, M3 = 350)).

when the robot is driving does net remain constant, and it is impossible to accurately predict the degree. Accurate mechanical analysis of driving on granular surface with these fluid properties is challenging. The Taguchi method allowed robot to be designed robustly in these situations.

However, this experiment was conducted only on particles between 0.2mm and 0.7mm. Theses particle sizes were selected to show results for desert, a representative terrain that demonstrates the advantages of screw-based crawling robot. Verification experiments showed that this work was valid. Based on this, experiments on more diverse granular particle sizes should be conducted to generalize the experimental results. As mentioned in Discussion, experiments with the degree to which the screw-wheels are buried will also need to be carried out to apply in more diverse granular surface. This additional future work will lead to the development of the speed of the screw-based crawling robot on the overall granular surface.

VI. CONCLUSION

In this study, a robust design of screw wheels was investigated to improve the driving speed of a screw-based crawling robot on a granular surface. For the robust design, the Taguchi method was applied to the shape of the screw wheel. The Taguchi method was accomplished via an $L_9(3^4)$ orthogonal array for four design parameters and two user conditions. Consequently, the robust modeling of the design parameters was set at 3, 3, 1, and 1 levels. To check the validity, a verification experiment was conducted. According to the results of the verification experiment, the optimized model showed an improved speed when compared to the No. 6 model, which was the most similar to the initial model. The optimized model showed an average performance improvement of 18.113% over the No. 6 model. The comparison graph is shown in Fig. 9. The S/N ratio of the optimized model is 36.266 dB, which is the best performance when compared to the previous models. The S/N ratio analysis of the design parameters showed that the most sensitive factor was the number of spirals; the higher the number, the lower the performance. The height of the blade also showed a high sensitivity, improving the performance as it increased. In the case of user conditions, the sensitivity was low. Based on these results, a robust design using the Taguchi method was shown to be effective in improving the driving speed of a screw-based crawling robot on a granular surface.

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