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Optimal kinematic design of a mobile robotic platform that can navigate the stairs based on the rocker-bogie mechanism

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Abstract

The functions of navigating the stairs as well as crossing the projected thresholds and/or obstacles on the room floor are required to the home service robots that are supposed to move around in the private house. To realize these functions, a few mechanical robotic platforms have been designed based on the rocker-bogie mechanism. However, the motion of climbing upstairs still shows a certain amount of joggling and shaking up and down. The optimization of the kinematic parameters of the rocker-bogie mechanism is required. Actually, it has total seven parameters to optimize: four link lengths and three wheel diameters. This paper deals with the finding of the optimal values for these seven parameters that minimize basically the vertical shaking amount of the kinematic center when it navigates the stairs. Two case studies of optimizing the rocker-bogie mechanism are presented in this paper. In the first case study, all three wheels are actuated independently when it navigates the stairs as in the case of home service robots. In the second case study, all three wheels are passive and the part of the rocker-bogie mechanism body is pulled up by the external force as in the case of shopping carts. The optimization index of each case study is defined, respectively, and the optimal values are found by using Taguchi methodology. Finally, the experimental results are shown to verify the optimization methodology.

Keywords: *optimal kinematic design, Taguchi methodology, stair-climbing robot, rocker-bogie mechanism*

1. Introduction

These days, various mobile robots are being developed and researched in a number of fields. Mobility is an essential element of the mobile robots. The travel system for the mobile robots can be classified in two types, leg and wheel. The leg locomotion has good adaptability for rough terrain. However, it also has disadvantages of low speed relative to wheels, complexity of control and manufacture, inefficient weight. On the contrary to the leg locomotion, wheel driving systems can travel at high speed. Also they are easy to control and manufacture and with light weight, but low adaptability to a rough terrain.

A new wheel suspension system is designed to complement the both types of locomotion with a passive linkage wheel system by NASA, The MERs (Mars Exploration Rover – Sojourner, Sprit, Opportunity) developed by NASA use the early type of a passive linkage wheel system, also known as the rocker-bogie mechanism [1-3]. The linkages and passive joints of the mechanism connected a robot body with wheels, as Fig. 1 shows. The rocker-bogie mechanism improves the robot's rough terrain adaptability as much as the leg locomotion.

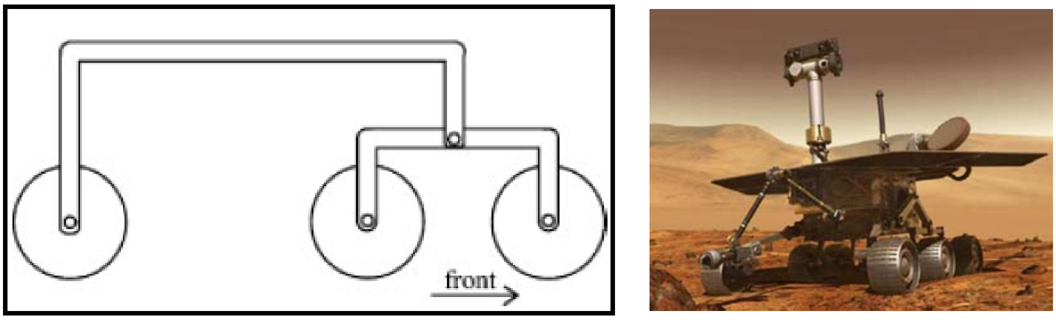


Figure 1. The rocker-bogie mechanism and the MER

This study applies and optimizes the rocker-bogie mechanism to an indoor mobile robot's travel system and a cart mechanism to climb stairs. Therefore, both the robot's travel system and the cart have a common point, the rocker-bogie mechanism to navigate the stairs as well as to cross the projected thresholds and obstacles on the room floor. Simultaneously, there is also a difference between them. Although the robot climbs stairs keeping all the wheels' traction forces in contact with the floors, the cart should be pulled up to climb stairs by external forces. The robot has independently actuated wheels, but the cart has passive wheels.

There are a few optimization studies about passive linkage wheel systems. Thueer studied optimization control of motor torques for stable driving on a rough terrain [4-6]. The robot distributes the motor torques for stable driving with little wheel slip. The optimization researches are concentrated on the control problem except for a robot mechanism design. If the robot is designed optimally, it can be controlled with efficient motor torque and traction forces.

There are also link parameter optimization studies of the passive linkage wheel systems to climb stairs or steps. Meghdari optimized link parameters of another passive linkage wheel system called the shrimp mechanism. It has advantage on climbing stairs with efficient energy [7-10]. Also, because the link parameter is optimized separately for different sizes of stairs, there are different optimization results for different stairs. However, the robots are optimized with all the same size wheels and a few link parameters.

The study presented in this paper has different and advanced points compared to previous work. The robot and the cart, which are optimized in a view of kinematics, have different wheels' sizes to include the wheels' radius as link parameters to optimize. Also the objective function of the robot optimization defined differently from the one of the cart, because they have different purposes and conditions. In this paper the Taguchi method is applied with three different sizes of stairs as a noise factor to optimize the rocker-bogie mechanism for the robot and the cart. Finally to verify the simulation result according to Taguchi method, the experiment is performed with optimally designed cart is manufactured and experimented.

2. Optimization process with the Taguchi method

This chapter introduces the optimization process with the Taghchi method. To optimize the stair climbing ability of rocker-bogie mechanism, two cases of stair-climbing situations are suggested. Therefore the optimization objective function is defined separately for each case, and the Taguchi method is applied for the optimization sequence.

2.1. Application of the Taguchi Method

The Taguchi method was originally developed for quality engineering and for evaluation and improvement of a product's robustness, tolerance specifications, and quality management of a production process. It does not draw upon complicated probability or statistical analysis. This methodology also can be applied to kinematic parameter optimization, which this paper presented. With this method, an optimized solution can be obtained by design of experiments, which normally demands complicated mathematical expansion in the theoretical approach.

The Taguchi method divides the independent variables into controllable factors and noise factors. Controllable factors can be maintained to a desired value, while noise factors may not be controlled. The Taguchi method can realize a robust design, which can maintain high performance as well as insensitivity to noise factors. In this section 2, the Taguchi method is applied in designing the simulations for maximizing the ability of stair-climbing.

2.2 Problem statement for each case

Stair-climbing with Rocker-bogie mechanism can be divided into two cases. In the first case, all wheels are actuated independently so Rocker-bogie mechanism body climbs stair by itself as in the case of home service robots (case 1). The second case, all wheels are passive, and rocker-bogie mechanism body is pulled up by external force as in the case of shopping cart (case 2). Each case is assumed as fully different situation, this makes difference of kinematic systems and optimization problem conditions.

2.2.1. Noise Factor

In this optimization problem statement, three shapes of stairs to be climbed by rocker-bogie mechanism are chosen as noise factor. Fig. 2 shows the scheme of stairs sizes.

2.2.2. Kinematic Model

In case 1, the center of mass (CM) of mechanism is located at the center of Link 2, allowing for mechanism similarity of MER series. And in case 2, CM is fixed at Link 1, this originated from the cargo fixation at Link 1. The kinematic models of case 1 and 2 are described in Fig. 3.

For rocker-bogie mechanism, it has 2-D kinematic structure. In this model, seven design variables are selected as each wheels' radius (R_1, R_2, R_3) and length parameters of Link 1 and Link 2(l_1, l_2, l_3, l_4).

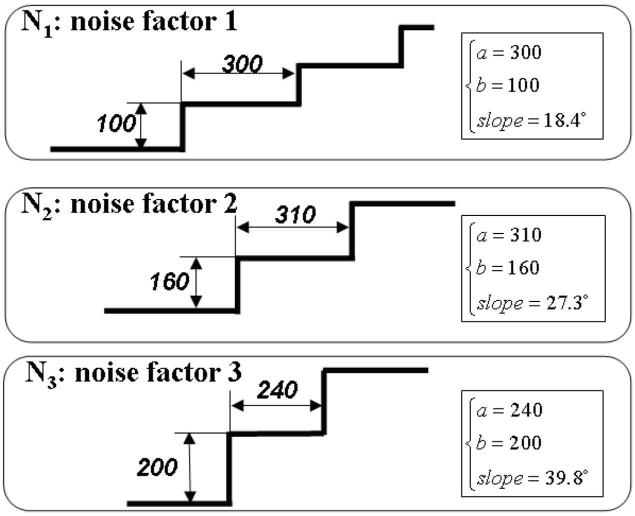
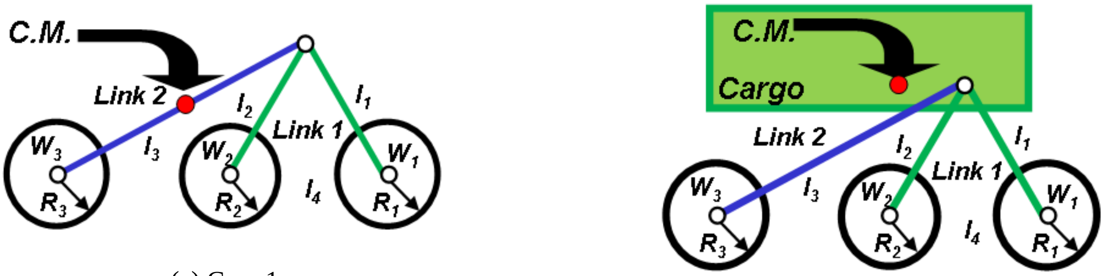


Figure 2. types of stair conditions



(a) Case 1

(b) Case 2

Figure 3. Kinematic structure of rocker-bogie for the optimization problem statement of case 1 and 2

2.2.3. Objective function

Objective functions get differ when they get different cases. For case 1, if the CM’s path gets more displaced form the straight line of stair’s inclination, the rocker-bogie mechanism’s movement is more non-uniform. So the objective function for case 1 is defined as the area between stair’s inclination line and rocker-bogie mechanism’s CM trace line. To minimize this area is optimization target of case 1. The defined objective functions for case 1 is as below

$$\min\ f\left(l_1,l_2,l_3,l_4,R_1,R_2,R_3\right)=(Area\ between\ C.M.'s\ \ pass\ and\ straight\ line)$$

$$\begin{gathered}
\text{subjected to}\\
25 \le R_i \le 244 \quad \left(i=1,2,3\right)\\
l_4 > R_1 + R_2\\
\sqrt{{R_2}^2+(b+R_1-R_2)^2} \le l_4 \le \sqrt{(a-R_1)^2+(R_1-R_2)^2}\\
l_1+l_2 \ge l_4\ ,\ l_2+l_4 \ge l_1\ ,\ l_4+l_1 \ge l_2\\
R_i \le l_i \le 1000 \quad \left(i=1,2,3\right)\\
l_3-R_3 > l_2+R_2
\end{gathered} \tag{1}$$

For case 2, to get most stabilized condition for cargo area, 2 concepts are applied to objective function as follows: a. Stabilize CM’s trace line as much as possible, b. Minimize Cargo’s maximum angle of inclination. So minimize deviation of difference between CM’s trace line and stair’s inclination line and maximum angle of cargo is objective function of case 2. (The weighting factor for each subject is 0.5.). The defined objective functions for case 2 is as below:

$$\min\ f\left(l_1,l_2,l_3,l_4,R_1,R_2,R_3\right)=0.5\times\textit{(Deviation of difference between C.M.'s pass and stair's inclination line)}$$
$$+\ 0.5\times\textit{(Maximum angle of cargo)}$$
$$\text{subjected to}$$
$$R_i \le l_i \le 500 \quad \left(i=1,2\right) \tag{2}$$
$$25 \le R_i \le 244 \quad \left(i=1,2,3\right)$$
$$l_4 > R_1 + R_2$$
$$l_1+l_2 \ge l_4\ ,\ l_2+l_4 \ge l_1\ ,\ l_4+l_1 \ge l_2$$
$$l_3 - R_3 > l_2 + R_2$$

The separation of driving mechanism and purpose of each case also make different constraint. Firstly, both cases get constraints of size limitations. Home service robots are referred for case 1 and commercial shopping carts are referred for case 2. For case 1, constraints for stabilization for each wheel's position added. Finally, constraints about structural limitation (position limitations for links and wheels) added for both cases. The constraint equations for case 1 and case 2 are as equation (1) and (2) shows. In section 2.2, problem statements for different cases are established. With this for a basis, optimization for each case will be completed in section 2.3.

2.3. Optimization by the Taguchi method for cases

In the optimization process, the Taguchi method is used for previously defined optimization problem. This optimization problem is 'smaller-the-better' problem, so the target of both cases is minimizing objective function. For this, three shapes of stairs are obtained as noise factors, and S/N ratio should be maximized from these noise factors. The definition of S/N ratio is as below:

$$SN = -10\times\log\left|\frac{y_1^{\,2}+y_2^{\,2}+y_3^{\,2}}{3}\right| \quad \left[dB\right] \tag{3}$$
$$y_i:\text{Tracking Error with } i\text{-th noise factor}$$

The levels of design variables for two cases selected by preceded research. Optimization processes with the Taguchi method are repeated for each case. To get final optimized result, levels of design variables in Table 1 are arranged for every optimization.

For case 1, $\mathbf{L}_{18}(2^1\times 3^7)$ orthogonal array is selected. $\mathbf{L}_{18}(3^7)$ orthogonal array is applied to case 2. The obtained result of these optimize problem statement is described at section 3.

Table 1. Level of the design parameters

level	l_1	l_2	l_3	l_4	R_1	R_2	R_3
#1	155	85	225	180	25	70	45
#2	170	100	240	195	40	85	60
#3	185	115	255	210	-	100	75

(a) Case 1 – 1st optimization

level	l_1	l_2	l_3	l_4	R_1	R_2	R_3
#1	185	75	215	190	25	60	55
#2	190	80	220	195	30	65	60
#3	195	85	225	200	-	70	65

(b) Case 1 – 2nd optimization

level	l_1	l_2	l_3	l_4	R_1	R_2	R_3
#1	184	68	213	191	25	61	64
#2	187	71	216	194	28	64	67
#3	190	74	219	197	-	67	70

(c) Case 1 – 3rd optimization

level	l_1	l_2	l_3	l_4	R_1	R_2	R_3
#1	186	70	215	193	25	63	66
#2	187	71	216	194	26	64	67
#3	188	72	217	195	-	65	68

(d) Case 1 – 4rh optimization

level	l_1	l_2	l_3	l_4	R_1	R_2	R_3
#1	350	200	550	375	60	60	60
#2	400	250	600	450	75	75	75
#3	450	300	650	525	90	90	90

(e) Case 2 – 1st optimization

level	l_1	l_2	l_3	l_4	R_1	R_2	R_3
#1	350	200	550	415	60	90	60
#2	400	250	600	450	75	105	75
#3	450	300	650	485	90	120	90

(f) Case 2 – 2nd optimization

3. Optimization Result

3.1 Optimization result of case 1

After proceeding optimization for case 1, the design variables, the kinematic structure shape of rocker-bogie, and CM's path for each stair for case 1 acquired as below. Table 2 shows the result of design parameter optimization. In Fig. 5, red line means the slope of stair, and line with small blue circle is path of cargo's CM.

Table 2. Optimized design variables for case1

l_1	l_2	l_3	l_4	R_1	R_2	R_3
187	71	216	194	25	64	67

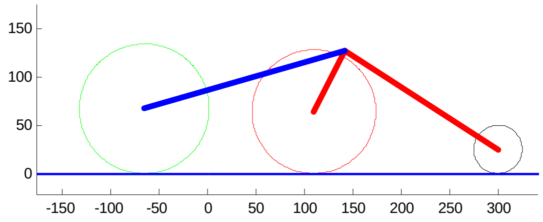
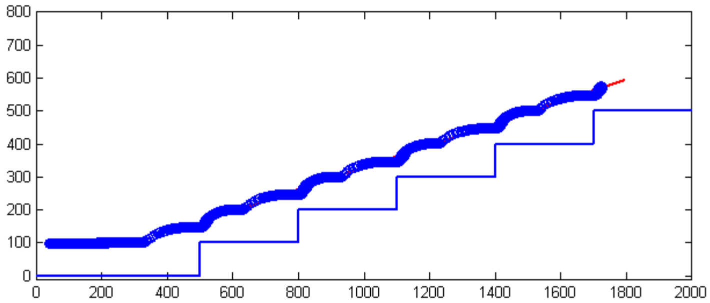
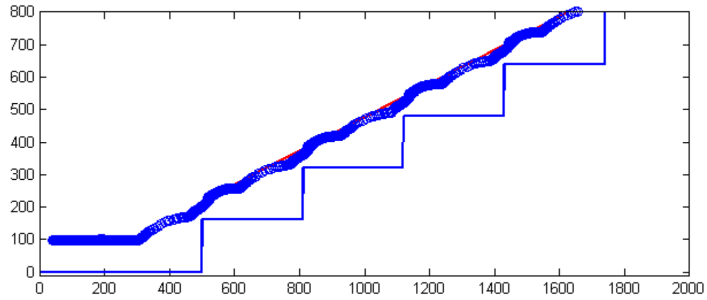


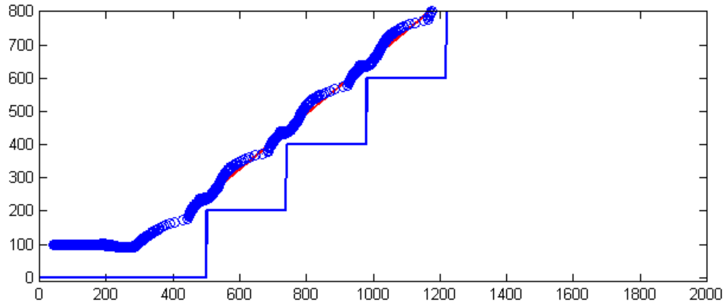
Figure 4. Optimized result of kinematic structure of the rocker-bogie for case 1



(a) stair: 300/100



(b) stair: 310/160



(c) stair: 240/200

Figure 5. CM paths of the optimized rocker-bogie for case 1

3.2 Optimization result of case 2.

As the same manner of section 3.1, the result of the optimization for case 2 is obtained. Table 3 shows the optimized results: design variables, the kinematic structure shape of rocker-bogie, and CM's path for each stair. In Fig. 7, red line means the slope of stair, and line with small blue circle is path of cargo's CM, as same as Fig. 5 in case 1,

Table 3. Optimized design variables for case 2

l_1	l_2	l_3	l_4	R_1	R_2	R_3
400	300	550	450	90	120	75

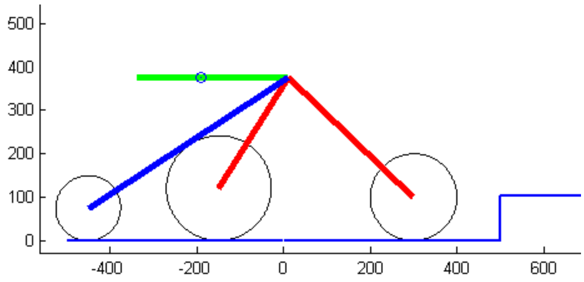
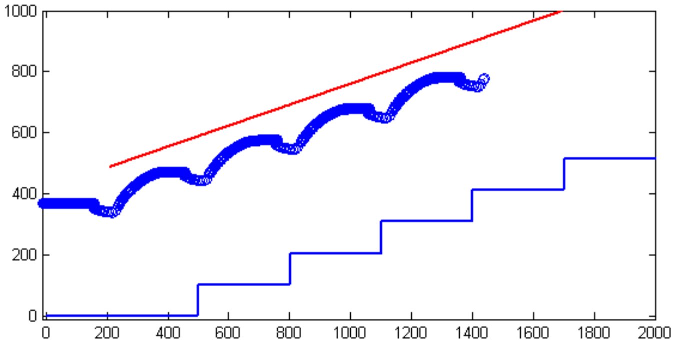
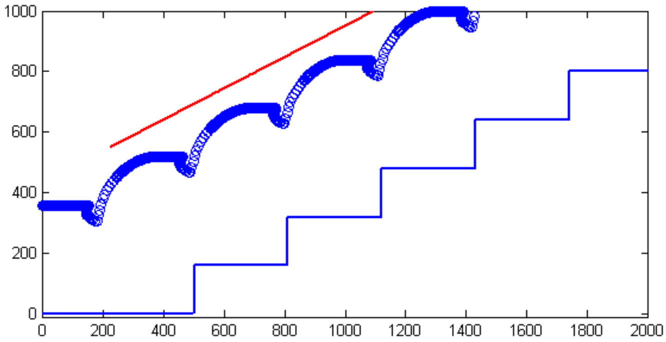


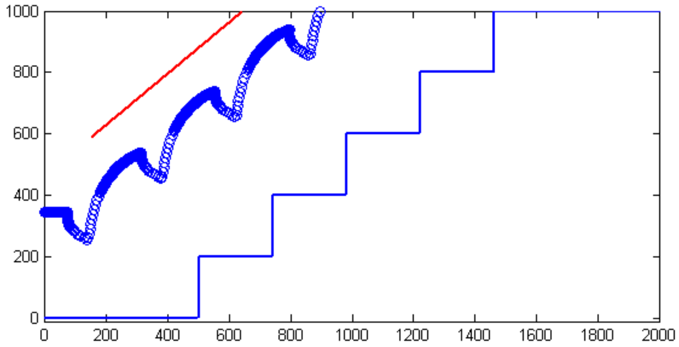
Figure 6. Optimized result of kinematic structure of the rocker-bogie for case 2



(a) stair: 300/100



(b) stair: 310/160



(c) stair: 240/200

Figure 7. CM paths of the optimized rocker-bogie for case 2

4. Experiment for optimization verification for case 2

In this section, the experiment to verify the simulation result of case 2 is introduced. For the experiment, the cart designed with optimized rocker-bogie structure is manufactured as Fig. 8 shows.

4.1 Production of Rocker-Bogie structure

Manufactured cart which designed for stair-climbing with optimized design parameter has each link’s joint has bearings, and cargo which is fixed at Link 1 allowing for application situation of case 2.

Figure 8. The photo of manufactured rocker-bogie cart (case 2)

4.2. Noise Factor

Three shapes of stairs selected as noise factor are produced for experiment. Each stair structure consists of 5 steps as Fig. 9 shows.

(a) N_1 (300/100) (b) N_2 (310/160) (c) N_3 (240/200)

Figure 9. Shapes of stairs for noise factor

4.3. Measuring Maximum angle and path of CM

To measure maximum angle of cargo posture, the digital clinometer is attached. And laser tracker system and marker used to get the path of CM of rocker-bogie structure. The Fig 10 shows the attached measuring instruments.

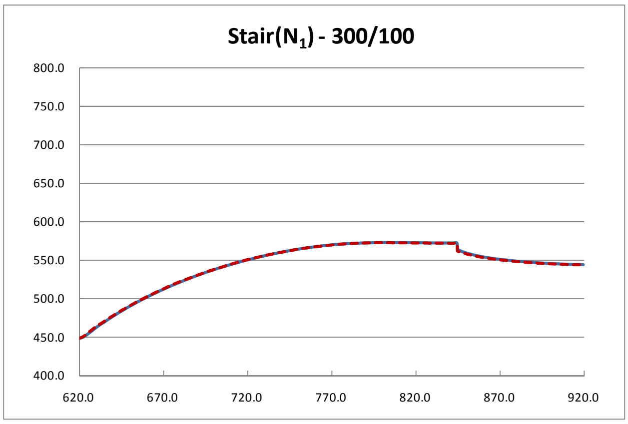
(a) Digital clinometer (b) Laser tracker marker ball

Figure 10. Measuring instruments attached on the cargo

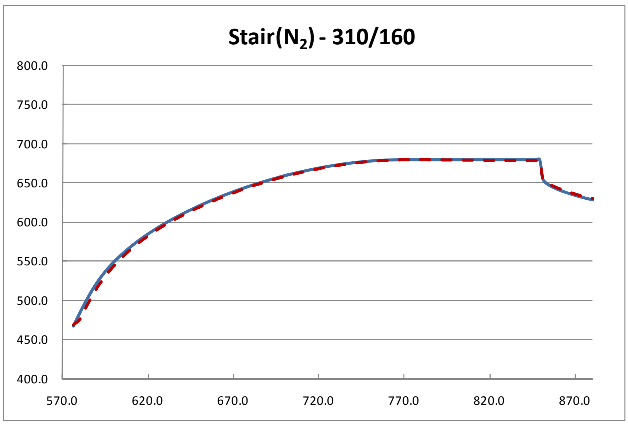
With these instruments, maximum angle and path of CM are measured 5 times for each stairs.

4.4. Experiment Result

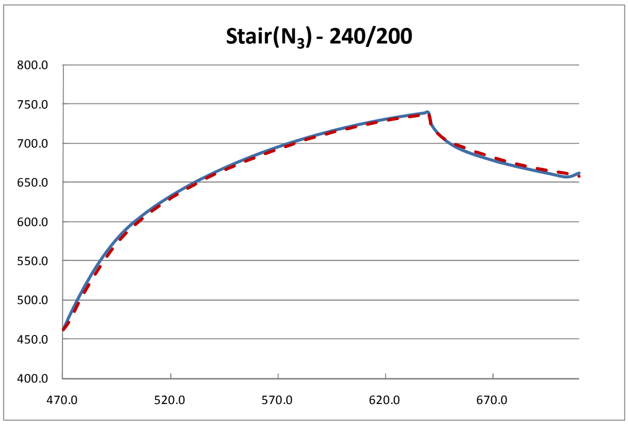
With the result of experiment, averages of experiment results are compared to simulation result. The details of comparison are as bellow.



(a) N_1 (300/100)



(b) N_2 (310/160)



(c) N_3 (240/200)

Figure 11. Comparison of CM path

Fig. 11 shows the comparison between simulation data and measured data. Each graph shows one cycle of movement of rocker-bogie structure cart on stair. Red dashed line shows average path line of experiment, and blue solid line means path line of simulation.

Table 4. Comparison of maximum angles

	1st	2nd	3rd	4th	5th	Average
max. degree	28.5˚	29.7˚	29.2˚	29˚	29.6˚	29.2
error	+4.5˚	+5.7˚	+5.2˚	+5.0˚	+5.6˚	+5.2

(a) Stair: 300/100

	1st	2nd	3rd	4th	5th	Average
max. degree	41.7°	42.8°	43°	42.1°	42.6°	42.4
error	+5.7°	+6.8°	+7.0°	+6.1°	+6.6°	+6.4

(b) Stair: 310/160

.	1st	2nd	3rd	4th	5th	Average
max. degree	56.9	57.2	56.9	56.8	54.9	56.5
error	+7.7	+8.0	+7.7	+7.6	+5.7	+7.3

(c) Stair: 240/200

Table 5. Comparison of noise factor and S/N ratio between simulation and experiment

	Noise Factor			S/N ratio
	300/100	310/160	240/200	
Simulation	0.2508	0.3666	0.5118	8.1571
Experiment	0.2961	0.4163	0.5602	7.1755

With the comparison between simulation result and experiment result, errors occurred at S/N ratio. Table 4 shows the errors of experiments with different stairs. Accuracy of the shape of stair and shaking of rocker-bogie structure and stair seem to be the sources of error occurrence. They caused +5~7 degrees of maximum angle's error, and it magnified the error of noise factor and S/N ratio finally. Though there are errors between simulation and experiment result, they maintain overall tendency and uncertainty of experiment should be considered. Therefore, these errors are acceptable.

5. Conclusion

This paper has examined the kinematic design parameter optimization of rocker-bogie mechanism for an indoor robot and a stair-climbing cart. The optimizations of the link parameters are executed for both the robot and the cart. The optimizations are performed with the different objective functions and constraints for the two application cases. Both optimizations are performed with common optimization method - the Taguchi method. Three kinds of stair are selected as a noise factor, and each case has the smaller-the-better objective function. With the Taguchi method, optimized kinematic design parameters of rocker-bogie mechanism are obtained. To verify the simulation result, the real stair-climbing cart manufactured. And the experiments results with the clinometer sensor and laser tracker system indicated that the optimization process with Taguchi method presented in this paper is appropriate. As a future work, the verification experiment with independently actuated wheel system is underway.

Acknowledgments

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