Springer

KSME

Journal of Mechanical Science and Technology 27 (1) (2013) 125~132
www.springerlink.com/content/1738-494x
DOI 10.1007/s12206-012-1212-y

Optimal design of hand-carrying rocker-bogie mechanism for stair climbing †

Hee Seung Hong[1,♦], TaeWon Seo[2,♦], Dongmok Kim[1], Sunho Kim[1,*] and Jongwon Kim[1]

[1]*School of Mechanical and Aerospace Engineering, Seoul National University, Seoul, 151-742, Korea*
[2]*School of Mechanical Engineering, Yeungnam University, Gyeongsan, 712-749, Korea*

(Manuscript Received January 24, 2011; Revised August 8, 2012; Accepted August 9, 2012)

Abstract

Transporting heavy packages while climbing stairs can be a very difficult or dangerous task. In situations where this task is frequently required such as construction sites, workers would use equipment such as a back rack for convenience, but still it becomes a difficult task as the weight increases. In this paper, we propose a stair climbing hand-carrying cart based on the rocker-bogie mechanism. We conduct an optimal design of the kinematic variables of the rocker-bogie mechanism for stable stair climbing using Taguchi methodology. Fluctuations and a tilted angle during stair climbing are considered to formulate the objective function. Three different shapes of typical stairs are selected as user conditions to determine a robust optimal solution. The results are verified by experiments using a testing set-up of three stair profiles, and the experimental results are compared with simulation. We expect that the results of this research can be applied to stair climbing robot design.

Keywords: Optimal design; Rocker-bogie mechanism; Stair climbing; Taguchi methodology

---

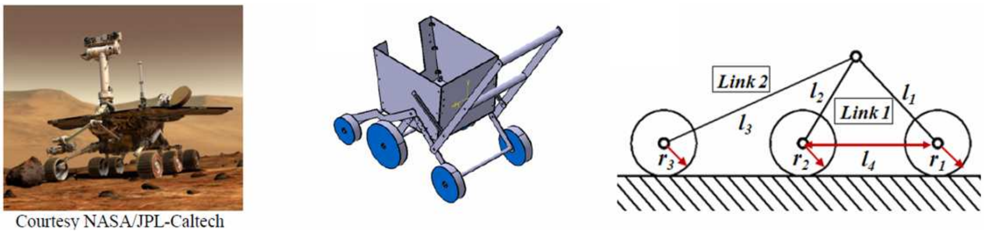
1. Introduction

Moving heavy packages using stairs is a common difficult task in some situations. For example, at a construction site, workers must transport their equipment or building materials up and down stairs. This is since small construction sites generally do not have an elevator to move heavy packages. Therefore, workers need to carry these packages using back racks up the stairs causing risks of accidents or injuries. Carts may be desired as a substitution, but ordinary carts used to move packages lack stair-climbing ability since they are very unstable when climbing stairs. A hand-carrying cart with a new concept can be a solution to move heavy packages up stairs.

Several mechanisms can be considered for use in this hand-carrying stair climbing application. A star-wheel mechanism [1-4] uses a triangular or a rectangular link with small wheels at the end of the link, and a link with wheels rotates when the mechanism climbs. This star-wheel mechanism is compact and simple, but there is fluctuation during climbing and not all stairs can be climbed due to the fixed link dimension. A mechanism from Galileo Mobility Instruments [5, 6] climbs stairs using a reconfigurable caterpillar shape; thus, it can climb various shapes of stairs. However, the Galileo mechanism needs an actuator for the reconfiguration, so the mechanism cannot be designed in a fully passive way. The Blanco stair climbing mechanism [7, 8] is composed of a large wheel with protruding legs whose length is adjusted passively by an external condition. The mechanism is heavy due to its large wheel, so it is not suitable for hand-carrying applications.

The rocker-bogie mechanism [9, 10] is a six-wheeled mechanism with compliant links and is well-known for its good obstacle adaptation ability. The rocker-bogie mechanism was used as the base platform of the Mars exploration rovers (Sojourner, Sprit, and Opportunity) of the National Aeronautics and Space Administration (NASA) [11, 12]. Due to its mechanical simplicity and adaptability to various external conditions, the rocker-bogie mechanism has a significant advantage for hand-carrying stair climbing applications. To maximize climbing performance, an optimal design of the mechanism is required to achieve robust and stable climbing. But the most of NASA's researches are focused on the kinematic state estimation based on the torque and slipping detection [13, 14]. We performed an optimal design of a rocker-bogie mechanism for a stair climbing application using Taguchi methodology. Four kinematic parameters of links and three of wheels were optimized to achieve stable and robust climbing. We selected the objective function considering both fluctuations of a cargo and maximum tilting angle of the cart during stair climbing. Three different sets of stair dimensions were considered as typical user conditions. As a result, the stair climbing performance of the rocker-bogie mechanism was improved by 33.5% (1.255 dB) through a two-step optimization.

♦ These authors made equal contributions as first author.
*Corresponding author. Tel.: +82 2 880 7144, Fax.: +82 2 875 4848
E-mail address: sunkim@rodel.snu.ac.kr
† Recommended by Editor Sung-Lim Ko



(a) (b) (c)

Fig. 1. Rocker-bogie mechanism: (a) opportunity mars rover based on rocker-bogie mechanism; (b) configuration of the rocker-bogie cart (A: wheels of the rocker-bogie mechanism, B: handle, C: cargo); (c) configuration of the rocker-bogie mechanism and its kinematic variables.

Experiments to measure the climbing path and the angle of the cart on the three different stair profiles were conducted to verify the performance of the proposed mechanism.

The advantages of Taguchi methodology [15] are as follows:

- Can identify the sensitivity of the design variables (control variables) through sensitivity check sequence.
- Derive optimal solution which has the least fluctuation of performance caused by the noise factors.
- Minimize the number of tests to get result.

Based on this methodology, we can use rocker-bogie mechanism with more practical means.

The rest of the paper is organized as follows. In Section 2, objective function, constraints, and user conditions are introduced. The procedure and results of the optimal design are described in Section 3. Two-step optimizations were conducted, and the sensitivity of each parameter is presented. The experimental results of climbing on three different stair profiles are given, and simulation results are presented in Section 4. Our conclusions are given in Section 5.

2. Problem definition

2.1 Rocker-bogie mechanism

A rocker-bogie mechanism is a six-wheeled driving mechanism that has pair of two passive joints with wheels attached to each link. Every wheel can contact the ground simultaneously on uneven terrain; therefore, this mechanism can maintain a stable condition. The shape of the rocker-bogie mechanism is shown in Fig. 1(a).

A hand-carrying cart based on the rocker-bogie mechanism is shown in Fig. 1(b). The cart is composed of wheels based on the rocker-bogie mechanism, a handle, and cargo.

The configuration of the rocker-bogie cart is shown in Fig. 1(c). Two front wheels (w_1 and w_2) are attached to link 1, and one rear wheel (w_3) is attached to link 2. The two links are connected by a passive rotating joint. Cargo is fixed to link 1, so we assumed that the center of mass (CM) is fixed to link 1. The rocker-bogie cart mechanism has a three-wheel kinematic configuration on the left and right sides.

In our design problem, components of the kinematic shape were used as the design parameters. Seven design parameters were selected as shown in Fig. 1(c). Four parameters of the link dimensions (l_1, l_2, l_3, l_4) and three parameters of the radii of the wheels (r_1, r_2, r_3) were optimized using the optimization procedure described in Section 2.2.

2.2 Optimal design problem

2.2.1 Objective function

To obtain the most stabilized cargo condition, two components were considered to define the objective function. First, the objective of the optimal design is to minimize fluctuation during climbing. This can be measured by checking the deviation between a straight line with a slope angle and the path of the CM during stair climbing. This geometry is shown in Fig. 2(a). The second objective is to minimize the maximum tilting angle during climbing as shown in Fig. 2(b). Since the hand hand-carrying work is strongly affected by the tilting angle, it is also meaningful to consider the tilting angle as the objective function. These two components are considered with the same weightings to define the objective function as follows:

$$J = 0.5 \times \frac{\int (y-\bar{y})^2 dt}{\int y^2 dt} + 0.5 \times \theta_{\max} \quad (1)$$

where y denotes the height data during climbing, $\bar{y}$ denotes the height of the straight line of the slope angle, and $\theta_{\max}$ denotes the maximum tilting angle of the cargo.

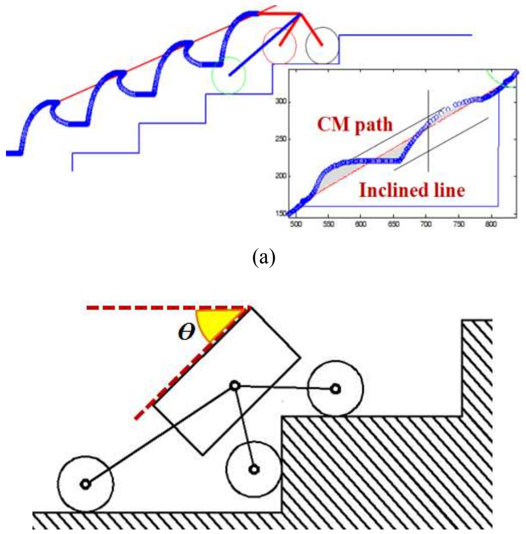
As described in the next section, there are three different sizes of typical stairs for the expected user conditions. Therefore, we obtained three different Js values for one rocker-bogie cart dimension. The final objective function is defined by using the smaller-the-better signal-to-noise (SN) ratio as follows:

$$SN = -10\log\left|\frac{J_1^2 + J_2^2 + J_3^2}{3}\right|. \quad (2)$$

By adopting this SN ratio, we simultaneously minimized the mean value and deviation of each Js [15].

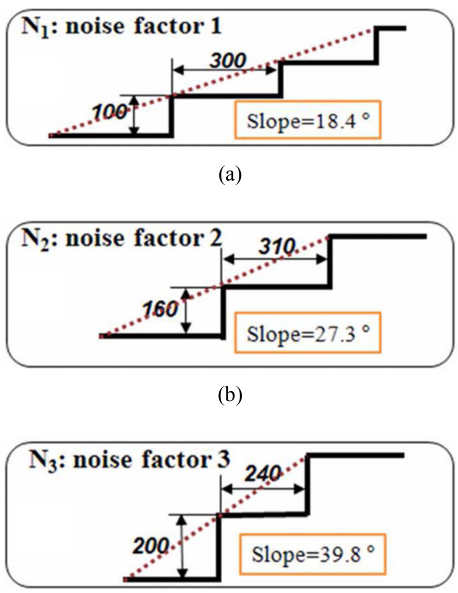
2.2.2 User condition (noise factor)

In this optimal design problem, three critical stair profiles



(a) (b)

Fig. 2. Two components of the objective function: (a) deviation between the linear climbing path of the stair and the CM path of the cart; (b) the maximum tilting angle of the cargo.



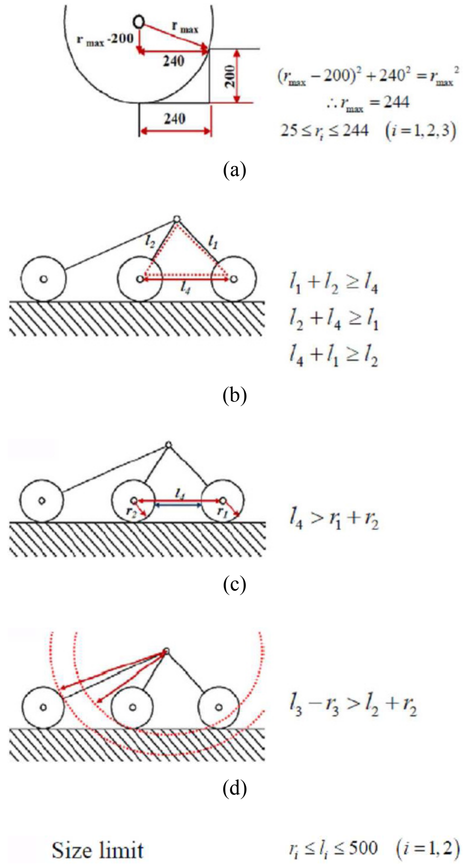
(a) (b) (c)

Fig. 3. Three critical stair profiles: (a) slight slope; (b) medium slope; (c) steep slope.

were selected as user conditions to determine the robust optimal solution. Fig. 3 shows the dimensions of the three profiles. The third stair shape is based on the extreme condition allowed by building construction regulations [16].

2.2.3 Constraints

There are five constraints from the geometric relations between links and wheels. The configuration used to calculate each constraint is shown on the left side of Fig. 4, and the



(a) (b) (c) (d) (e)

Fig. 4. Constraints: (a) maintenance contact on a horizontal plane; (b) formation of triangular-shaped link; (c), (d) avoidance of wheel overlap between wheels; (e) size limitation.

resulting mathematical expressions are shown on the right. We now describe the details of each constraint.

(a) Maintenance contact on a horizontal plane

The radius of each wheel should maintain contact with the stair tread for stable stair climbing. The upper radius limit is from the wheel contact condition (the extreme stair dimension is used as the worst case). The lower limit of the wheel radius is determined by commercial availability.

(b) Formation of triangular-shaped link

Parameters (l_1, l_2, l_4), which are related to link 1, are positioned in a triangular shape. Constraints are defined to maintain this triangular shape. The three inequalities shown on the right side were based on this limitation.

(c) Avoidance of wheel overlap between 1st and 2nd wheels

Due to the design complexity problem of the rocker-bogie cart, overlapping between wheels should be prevented. To avoid wheel overlapping distance between w_1 and w_2 (which means l_4) must be longer than the sum of r_1 and r_2.

(d) Avoidance of wheel overlap between 2nd and 3rd wheels

Wheel overlapping between the 2nd and 3rd wheel should be avoided. w_3 can be rotated along to the passive joint between link 1 and link 2, and w_2 and w_3 can be overlapped. From this condition, the constraint is defined as shown in Fig. 4(d).

(e) Size limitation

The size of the hand-carrying cart can be varied depending on the purpose of the cart. In this study, the size range of the rocker-bogie cart was limited based on the size of an ordinary commercial shopping cart [17]. In addition, the wheel radius was limited to be shorter than the link length for design simplicity.

3. Optimal design by Taguchi methodology

3.1 Taguchi methodology

Taguchi methodology was originally developed for quality engineering, and for the evaluation and improvement of a product's robustness, tolerance specifications, and quality management of the production process. Nowadays, the methodology is widely applied to solve any engineering optimization problem by using experiments [18-20]. Taguchi methodology has the advantages of experimentally-based optimization, sensitivity analysis, and the possibility of an optimization of an un-modeled system.

In this study, Taguchi methodology was used to optimize the kinematic variables of the rocker-bogie cart. Constraints were used to determine the initial values of the parameters, and the constraints were checked after choosing the optimal parameters.

3.2 Optimal design procedure

Optimal design is performed in two steps. First, an orthogonal array is used in each optimal design. Then, using sensitivity analysis, the optimal design parameters are determined.

3.2.1 Intermediate result of the optimal design

Levels of the design variables of optimal design were selected based on the constraints described in Section 2. Table 1 shows the selected design candidates for the optimal design. To use seven three-level design variable configurations in this optimal design, an L_{18} $(2^1 \times 3^7)$ orthogonal array was used. Table 2 and Fig. 5 shows the result of a simulation based on the L_{18} $(2^1 \times 3^7)$ orthogonal array. In Table 2, levels of the design variables represent the level of Table 1. Objective functions about three kinds of stair structures are obtained using this variables and Eq. (1). Finally, S/N ratios are calculated through Eq. (2).

From the SN ratio result of the L_{18} $(2^1 \times 3^7)$ orthogonal array, a sensitivity analysis on each kinematic parameter was performed as shown in Fig. 6. We note that the design parameters $D(l_4)$ and $F(r_2)$ have relatively higher sensitivities than the other design parameters. Therefore, we decided to perform the

Table 1. Selected design candidates for the optimal design.

Level	A (l_1)	B (l_2)	C (l_3)	D (l_4)	E (r_1)	F (r_2)	G (r_3)
#1	350	200	550	375	60	60	60
#2 <Initial>	400	250	600	450	75	75	75
#3	450	300	650	525	90	90	90

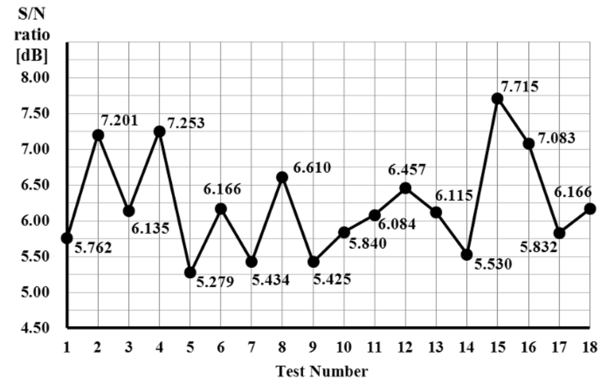


Fig. 5. Resulting SN ratio of L_{18} $(2^1 \times 3^7)$ orthogonal array formulated based on the design candidates listed in Table 1.

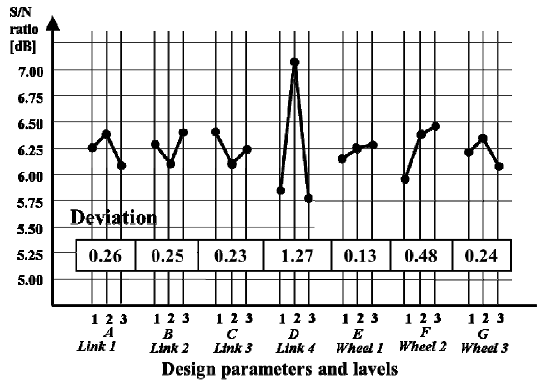


Fig. 6. Sensitivity analyses on each design parameter.

second optimal design for $D(l_4)$ and $F(r_2)$ while the other parameters were fixed. Note that *D2* and *F3* are the optimized values, and that they were used as level #2 in the next step of the optimal design.

3.2.2 Final result of the optimal design

In the second step of the optimal design, only $D(l_4)$ and $F(r_2)$ were used while the other parameters were fixed from the result from the previous optimal design process. The levels of the second optimal design are shown in Table 2.

The sensitivity analysis results of the second step are shown in Table 3 and Fig. 7. *D2* and *F3* have the highest SN ratio. The sensitivity result of design parameter *D* shows that *D2* is the final optimal value, and *F3* of the design parameter *F* reached the constraint limit. Therefore, the resulting parameters are considered to be the optimal values.

The maximum SN ratio can be calculated by using the sensitivity analysis result. Even though there is no combination of

Table 2. Result of each test from L_{18} (2^1X3^7) orthogonal array set up.

Test number	Level of the design variables							Objective fuction for each stair shape			S/N ratio (dB)
	A l_1	B l_2	C l_3	D l_4	E r_1	F r_2	G r_3	J_1: 300 × 100	J_2: 310 × 160	J_3: 240 × 200	
1	1	1	1	1	1	1	1	0.2376	0.4179	0.7515	5.762
2	1	2	2	2	2	2	2	0.2935	0.3757	0.5866	7.201
3	1	3	3	3	3	3	3	0.2457	0.4389	0.6909	6.135
4	2	1	1	2	2	3	3	0.2936	0.3742	0.5817	7.253
5	2	2	2	3	3	1	1	0.2639	0.4774	0.7694	5.279
6	2	3	3	1	1	2	2	0.2356	0.3858	0.7217	6.166
7	3	1	2	1	3	2	3	0.1987	0.4432	0.789	5.434
8	3	2	3	2	1	3	1	0.2932	0.4072	0.6348	6.61
9	3	3	1	3	2	1	2	0.2632	0.4718	0.7538	5.425
10	1	1	3	3	2	2	1	0.2545	0.4526	0.7156	5.841
11	1	2	1	1	3	3	2	0.1979	0.4096	0.7294	6.084
12	1	3	2	2	1	1	3	0.2927	0.4105	0.6512	6.457
13	2	1	2	3	1	3	2	0.2514	0.4422	0.6843	6.115
14	2	2	3	1	2	1	3	0.2125	0.442	0.774	5.531
15	2	3	1	2	3	2	1	0.2992	0.351	0.5431	7.715
16	3	1	3	2	3	1	2	0.324	0.3624	0.5924	7.083
17	3	2	1	3	1	2	3	0.258	0.4562	0.7131	5.832
18	3	3	2	1	2	3	1	0.209	0.3865	0.7295	6.166

Table 3. Design candidates of l_4 and r_1 and pre-determined design parameters at intermediate step.

Level	A (l_1)	B (l_2)	C (l_3)	D (l_4)	E (r_1)	F (r_2)	G (r_3)
#1	-	-	-	415	-	90	-
#2	400	300	550	450	90	105	75
#3	-	-	-	485	-	120	-

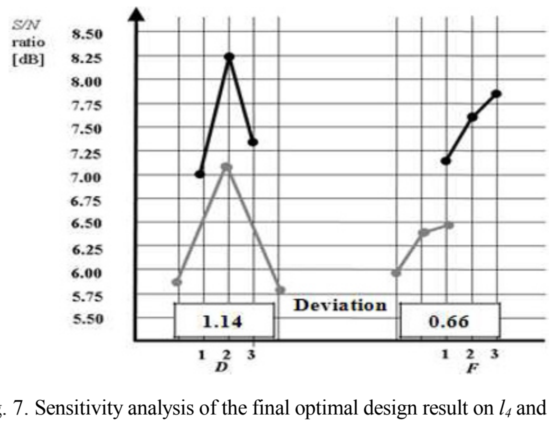


Fig. 7. Sensitivity analysis of the final optimal design result on l_4 and r_2.

the optimal kinematic parameters, we can calculate the final SN ratio by analysis. The average value of the SN ratio was calculated as follows:

$$\overline{SN} = \frac{1}{N}\sum_{i=1}^{N} SN_i \tag{3}$$

where SN_i is the SN ratio of each simulation and N is the total number of simulations. Then, the final SN ratio can be determined as follows:

$$SN_{\max} = \overline{SN} + (SN_{D2} - \overline{SN}) + (SN_{F3} - \overline{SN}) \tag{4}$$

where SN_{D2} and SN_{F3} are the SN ratios of $D2$ and $F3$ in the sensitivity result shown in Fig. 7. Using Eq. (4), the resulting SN_{max} was determined to be 8.534 dB.

3.2.3 Resulting optimal design parameters

Using the optimization result, the initial and optimized configurations of the rocker-bogie cart mechanism were determined as shown in Fig. 8. The SN ratio of the rocker-bogie mechanism was improved by 1.255 dB (33.5%) through two-step optimization. Based on this result, a real rocker-bogie cart was assembled and tested as described in Section 4.

4. Experimental verification

4.1 Experimental set up

Fig. 9 shows the experiment setup used to verify the optimal design result. The rocker-bogie cart was assembled based on the optimized design variables described in Section 3. A towing handle and cargo were included. Three different dimensioned stairs representing realistic user conditions were built for the experiment. Each stair structure consisted of five steps. To measure the maximum angle of the cargo posture, a digital inclinometer (Microstrain Fas-A) was used. A laser tracker system (Leica Absolute Tracker) was used to measure the CM

Table 4. Specification of the measurement system.

Inclinometer	FAS-A, Microstrain
Accuracy	± 0.7°
Resolution	< 0.1°
Repeatability	0.07 degrees (typical)
Update rate	40 Hz
Laser tracker system	Absolute tracker, Leica
Angular accuracy	± 15 μm + 6 μm/m
Sampling rate	1 kHz (maximum)
distance accuracy	± 10 μm

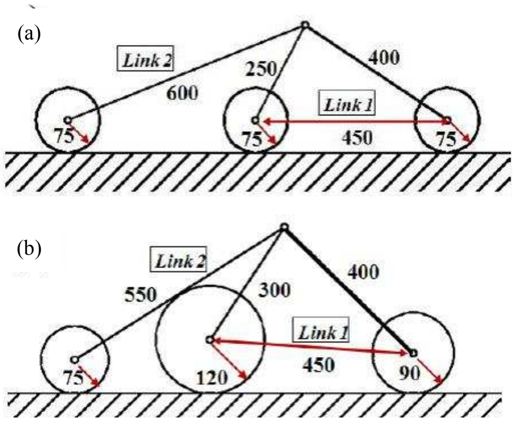


Fig. 8. Initial and optimized configurations of the rocker-bogie cart mechanism: (a) initial; (b) optimized.

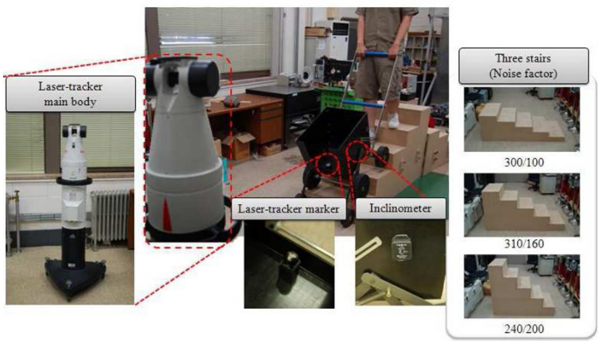


Fig. 9. Experimental set up for hand-carrying climbing and three stairs with different dimension.

path of the rocker-bogie cart. The detail of these instruments is shown in Table 4. The maximum angle and the CM path were measured five times for each stair type using these instruments. After the experiment, the averages of the maximum angle and the CM path data were used in the analysis.

4.2 Experimental result

4.2.1 Deviation between linear climbing path of the stair and CM path of the cart

Fig. 10 and Table 5 show a comparison between simulation data and experiment data. In Fig. 10, each graph shows one

Table 5. Averaging deviation of experiment and simulation.

	CM Path deviation		
	300/100	310/160	240/200
Experiment	0.0825	0.1049	0.1623
Simulation	0.0827	0.1048	0.1649
Error	-0.0002	+0.0001	-0.0026

Table 6. Maximum tilting angle of the cargo.

	Maximum tilting angle		
	300/100	310/160	240/200
Experiment	29.2	42.4	56.5
Simulation	24	36.0	49.2
Error	+5.2	+6.4	+7.3

Table 7. S/N ratio comparison between experiment and simulation.

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

cycle of movement of the rocker-bogie structure cart on the stairs. The red dashed line shows the average path line from the experiment, and the blue solid line shows the path line from simulation. The results of simulation and experiments are coincident. The maximum error is 8.16 mm on 310 × 160 stair structure. The main reasons of this precise experiment result are: (a) high quality of precision measurement instrument (as shown in Table 4), (b) slow and accurate moving on the stair structure to confirm contact and avoid collision impact between wheels and stairs.

4.2.2 Maximum tilting angle of cargo

In the maximum angle comparison between simulation and experiment, a noticeable error is evident as shown in Table 6, and the error increased as the slope angle increased.

4.2.3 SN ratio

By combining the previous two results, we can get the SN ratio. As expected the SN ratio has relatively large error of 1.02 dB due to the tilting angle error. Detailed result of the comparison is shown in Table 7.

Small errors occurred in the position measurement and large errors appeared in the maximum angle measurement. The mechanical joint clearance, the manual error of the worker, and the crash of the cart wheel with respect to the vertical plane of the stairs are considered to be the major sources of error. However, in our opinion, we still believe the result since the measured position error is in exact agreement with the simulation result even though there is relatively large error in the maximum tilting angle. The angular error should be im-

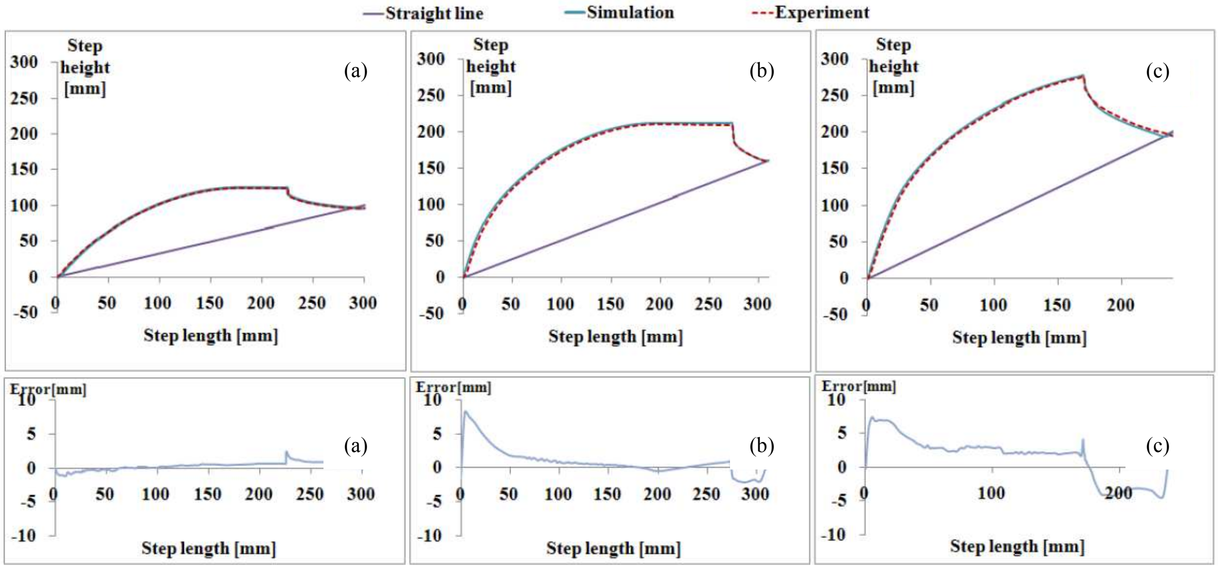


Fig. 10. CM path comparison of the experimental result and simulation: (a) 300 X 100 sized stair; (b) 310 X 160 sized stair; (c) 240 X 200 sized stair.

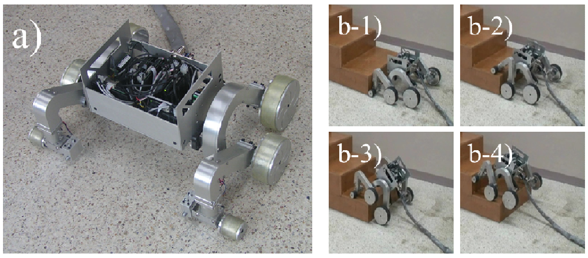


Fig. 11. (a) prototype of the mobile platform; (b) photos of climbing posture.

proved by re-designing the rocker-bogie cart.

5. Conclusions

We optimized the kinematic parameters of a rocker-bogie mechanism as a stair-climbing cart. The optimization was performed using Taguchi methodology, and the sensitivity analysis results were presented. The objective functions for cargo stability and the constraints were defined. Three typical stair profiles were used representing user environmental conditions to find a robust optimal solution. Compared with the original solution, the SN ratio of the rocker-bogie mechanism was improved by 1.255 dB (33.5%) through two-step optimization. And the most sensitive design variables throughout the optimization process are l_4 (angle between l_1 and l_2) and r_2 (radius of the second wheel). To verify the optimization result, a stair-climbing cart was built and tested. Even the tilting angle showed relatively large error, but the CM path showed that the simulation and experimental results are coincident.

Recently, several mobile robotic platforms for crawling uneven terrains are proposed for various application [21, 22]. As the next phase of our research, we also have developed an actuated mobile platform specialized for stair climbing [23]. In this research, rocker-bogie mechanism is applied and the parameters are optimized for best climbing performance. Currently we are testing the platform's stair-climbing ability and adjusting the torque and speed control algorithm for each wheel to maximize the performance. Fig. 11 shows the mobile platform prototype and the climbing sequence. Future work is to develop a new stair climbing mechanism and apply it to a mobile platform based on the previous experience.

Acknowledgment

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (No. 2012-0000348).

References

[1] M. Mohsen and M. M. Moghadam, Stair climber smart mobile robot (MSRox), *Autonomous Robots,* 20 (2006) 3-14.
[2] S. D. Herbert, A. Drenner and N. Papanikolopulos, Loper: A quadruped-hybrid stair climbing robot, *Proc. of Robotics and Automation*, Pasadena, CA, USA (2008) 799-804.
[3] R. W. Forsyth and J. P. Forsyth, Amphibious star-wheeled vehicle, *US Patent*, No. 3,348,518 (1967).
[4] S. T. Wyrick III, Stair climbing cart, *US Patent*, No. 2007/0075509 A1 (2007).
[5] http://www.galileomobility.com, *Galileo Mobility Instruments Ltd.*, 71520, Israel (retrieved at Jan. 10, 2011).
[6] Gil Michaeli. Transport mechanism, *US Patent*, No. 6,422,576 B1 (2002).
[7] E. E. Blanco, Stair climbing wheel chair, case study in creative design, *Study material 2.007 at Massachusetts Institute*

of Technology (1962).
[8] T. Ito, Simulation-based study using a stair climbing wheelchair, *Proc. of Asia International Conference on Modeling & Simulation*, Bandung, Bali, Indonesia (2009) 537-542.
[9] D. Bickler, The new family of JPL planetary surface vehicles, *in CNES Missions, Technologies, and Design of Planetary Mobile Vehicles*, D. Moura, Ed., Cepadues-Editions Publisher, Toulouse, France (1993) 301-306.
[10] D. Bickler, Articulated suspension systems, *US Patent*, No. 4,840,394 (1989).
[11] S. Hayati, R. Volpe, P. Backes, J. Balaram, R. Welch, R. Ivlev, G. Tharp, S. Peters, T. Ohm, R. Petras and S. Laubach, The rocky 7 rover: A mars sciencecraft prototype, *Proc. of IEEE International Conference on Robotics and Automation*, Albuquerque, NM, USA (1997) 2458 - 2464.
[12] J. Matijcvic, "Sojourner" the mars pathfinder microrover flight experiment, Space Technology, 17 (1997) 143-149.
[13] J. B. Balaram, Kinematic state estimation for a Mars rover, Robotica 18 (2000) 251-262.
[14] T. Iskenderian, Deployment process, mechanization, and testing for the mars exploration rovers, 37'h Aerospace Mechamisms Symposium (May 2004).
[15] G. S. Peace, *Taguchi methods - a hands on approach*, First Ed. Addison-Wesley Publishing Company, New York, USA, (1993).
[16] http://likms.assembly.go.kr/law/jsp/Law.jsp?WORK_TYPE=LAW_BON&LAW_ID=B2766&PROM_NO=22626&PROM_DT=20110117&HanChk=Y, The National Assembly of the Republic of Korea (retrieved at Jan. 24, 2011, in Korean).
[17] http://www.shopping-cart.com.tw, Shopping Cart Company (retrieved at Jan. 10, 2011).
[18] S.-H. Baek, S.-H. Hong, S.-S. Cho, D.-Y. Jang and W.-S. Joo, Optimization of process parameters for recycling of mill scale using Taguchi experimental design, *Journal of Mechanical Science and Technology*, 24 (10) (2010) 2127-2134.
[19] H.-K. Kim, J.-Y. Jeon, J.-Y. Park, S. Yoon and S. Na, Noise reduction of a high-speed printing system using optimized gears based on Taguchi's method, *Journal of Mechanical Science and Technology*, 24 (12) (2010) 2383-2393.
[20] H. Shin, S. Lee, W. In, J. I. Jeong and J. Kim, Kinematic optimization of a redundantly actuated parallel mechanism for maximizing stiffness and workspace using Taguchi method, *Journal of Computational and Nonlinear Dynamics*, 6 (1) (2011).
[21] B.-S. Kim, Q.-H. Vu, J.-B. Song and C.-H. Yim, Novel design of a small field robot with multi-active crawlers capable of autonomous stair climbing, *Journal of Mechanical Science and Technology*, 24 (1) (2010) 343-350.
[22] Y. Nakazato, Y. Sonobe and S. Toyama, Development of an In-pipe micro mobile robot using peristalsis motion, *Journal of Mechanical Science and Technology*, 24 (1) (2010), 51-54.
[23] D. Kim, H. Hong, H. S. Kim and J. Kim, Optimal design and kinetic analysis of a stair-climbing mobile robot with rocker-bogie mechanism, *Mechanism and Machine Theory*, 50 (2012) 90-108.

Hee Seung Hong received his M. S. in the School of Mechanical and Aerospace Engineering, Seoul National University at 2000, and is working toward a Ph.D. His research interests include robotic platform design, optimization and control.

TaeWon Seo is an assistant professor in the School of Mechanical Engineering, Yeungnam University, Gyeongsan, Republic of Korea. He received the Ph.D. degree in Mechanical Engineering, Seoul National University, in 2008. He was a Post-Doctoral Researcher at the Nanorobotics Laboratory, Carnegie Mellon University, in 2009. His research interests include creative robotic platform design, control, optimization and motion planning.

Dongmok Kim received his M.S. in the School of Mechanical and Aerospace Engineering, Seoul National University in 2006 and received his Ph.D. in Mechanical and Aerospace Engineering from Seoul National University in 2011. His research interests include climbing robotic platform design, optimization and control.

Sunho Kim is post-doctoral researcher in the School of Mechanical and Aerospace Engineering, Seoul National University where he received his Ph.D. in 2010. His research interests are robotic platform design and optimization.

Jongwon Kim is a professor in the School of Mechanical and Aerospace Engineering, Seoul National University, Korea. He received his B.S. degree in Mechanical Engineering from Seoul National University in 1978, and his M.S. degree in Mechanical and Aerospace Engineering from KAIST, Korea, in 1980. He received his Ph.D. degree in Mechanical Engineering from the University of Wisconsin-Madison, USA, in 1987. He worked with Daewoo Heavy Industry & Machinery, Korea, from 1980 to 1984. From 1987 to 1989, he was Director of the Central R&D Division at Daewoo Heavy Industry & Machinery. From 1989 to 1993, he was a Researcher at the Automation and Systems Research Institute at Seoul National University. His research interests include parallel mechanisms, Taguchi methodology, and field robots.