

Kinematic Optimal Design on a New Robotic Platform for Stair Climbing

Byung Hoon Seo, Hyun Gyu Kim, and Tae Won Seo

Abstract—Stair climbing is one of critical issues for field robots to widen applicable areas. This paper presents optimal design on kinematic parameters of a new robotic platform for stair climbing. The robotic platform climbs various stairs by body flip locomotion with caterpillar type main platform. Kinematic parameters such as platform length, platform height, and caterpillar rotation speed are optimized to maximize stair climbing stability. Three types of stairs are used to simulate typical user conditions. The optimal design process is conducted based on Taguchi methodology, and resulting parameters with optimized objective function are presented. In near future, a prototype is assembled for real environment testing.

Keywords—Stair climbing robot, Optimal design, Taguchi methodology, Caterpillar, Kinematic parameters.

I. INTRODUCTION

THESE days, various field robots are being developed with the purpose of building, explore the brush and vessel welding [1-3]. These field robots are aimed to doing what human can't do or hardly can do. It can be expected that development of these field robots enable various and sophisticated missions because existing industrial robots are concentrated on repeated working.

Although various field robot platforms are presented, still there are many shortcomings under the circumstance of obstacle. We can conclude that the firefighting robot that is developed recently can't deploy in various scenes because of their lacking ability which allows robot to overcome obstacles [4]. The robots that are developed for using in industrial sites are only able perform welding or painting on flat working condition because they can't overcome various obstacles [5]. As on case of mission failure, the robot that was deployed in Fukushima nuclear power plant were failed to check the radiation leak completely because of their limited ability of overcoming the obstacles [6].

It is essential for field robots to be sent to real sites to equip the ability of climbing stairs. It is important to overcome the natural obstacles such as rocks, trees and etc. but if the robot can't overcome the stairs, which is seen in our real life most common and difficult to overcome, the application range would be limited.

Jeon et al. [7] researched about biped robots walking stairs based on genetic algorithms. Kim et al. [8] conducted the optimization for climbing stairs using Rocker bogie structure of

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NASA. It's good example of research that Packbot [9] of iRobot conducted stair climbing with the method of caterpillar.

However, we need more research about climbing stairs with high speed and stability. This research deals with optimization design on new robot platform for climbing stairs using body flip locomotion based on caterpillar structure. For this process, the kinematic parameters are optimization for stair climbing stably using body flip locomotion.

Three types of stairs are defined as user condition and the optimization will be done by using Taguchi methodology [10]. Objective function is defined by the difference between accumulated values of straight line and trace of center of mass.

This paper is organized as follows. Section II explains the robot mechanism. Section III defines user conditions, design parameters and objective function by defining optimal design. Section IV presents optimization by using kinematic simulation based Taguchi methodology. Section V suggests the result of analyzed compared initial condition with optimization results. Section 6 concludes this research.

II. NEW FIELD ROBOT MECHANISM

A. Robot Design

Robot platform suggested in this paper has its purpose on climbing stairs with high speed using body flip locomotion. Fig. 1 shows the robot platform's 3D modeling. Robot is composed by caterpillar form of the main platform, rear wheel and links that joints both sides. On flat surface, the tread-wheels drive the robot, and steering is possible by skid-steering. Climbing stairs can be conducted by body-flip locomotion which rotates the main platform with link as lever; it will be explained with details in next section.

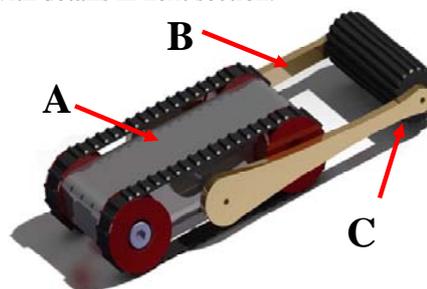


Fig. 1 Mechanism configuration of the robotic platform for stair climbing
A: main platform using caterpillar mechanism
B: Connecting link to the rear wheel
C: Rear wheel for high-obstacle overcoming

B. Stair Climbing Scenario

As mentioned above, robot climbs the stairs with body-flip

locomotion that rotates main platform. The scenario shows as Fig. 2. Robot can climb stairs with high speed using this locomotion. We highly expect that robot can control the relative position of main platform and climb various sizes of stairs if we modulated the velocity of caterpillar. We applied for patent in Korea at present [11]. The purpose of this research is the realization of climbing stairs with optimization of various design parameters assuming this locomotion.

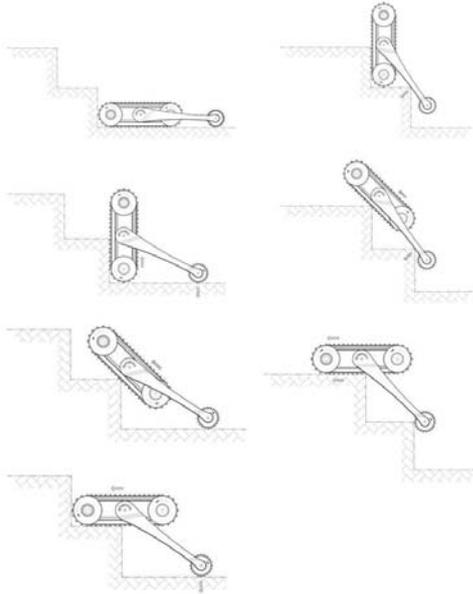


Fig. 2 Body flip locomotion scenario to climb stair

III. PROBLEM DEFINITION

A. Optimal Design Parameter

The purpose of this research is optimization on kinematic parameters of new robot platform for climbing stairs explained above. We defined 3 design parameters which are main platform's length (l_p) and height (h_p), and caterpillar's revolute velocity (ω_h). Fig 3 shows design parameters defined. We put the link's length that functions as lever as an exception while we concluded that the link has no influence on kinematic rotation.

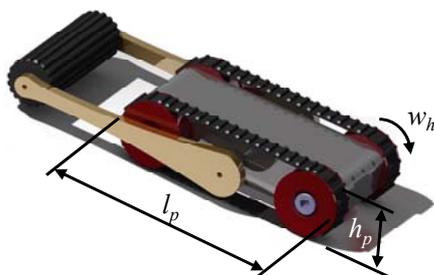


Fig. 3. Design parameters of the robotic platform
 A:Length of the main platform
 B:Height of the main platform
 C:Angular velocity of the track

B. Objective Function

It is very important to define the objective function for climbing stairs with stability. This research performs the optimization using objective function (1).

$$J_i = \frac{\int (y - \bar{y})^2 dt}{\int y^2 dt} \quad (1)$$

At this, y means the height of center of mass, \bar{y} means the value which is the straight line between y value of robot's initial condition and final condition. Fig. 4 shows the geometrical meaning of objective function and red line means y , yellow line means \bar{y} . This objective function is defined by difference of accumulated value between straight line and trace of center of mass. The smaller value of objective function means the more stable stair climbing. It is the function that has been proven by Kim et al [6].

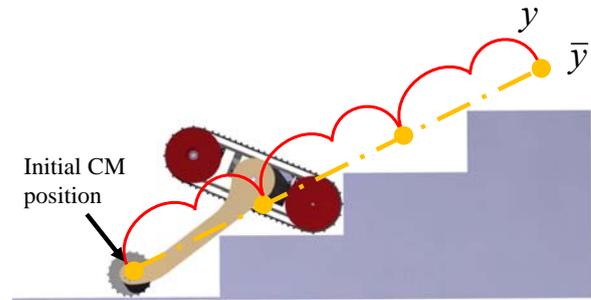


Fig. 4 Geometric meaning of objective function

C. User Condition (Noise factor)

There are various dimensioned stairs in buildings by building Act [12]. The ability of robot that climbs various stairs with stability is essential to be used in various situations. We defined three types of stairs in this research as user condition, and it shows Table I and Fig. 5. The purpose of this research is fine the design parameters that include the minimum value of objective function (1) about suggested three types of stairs.

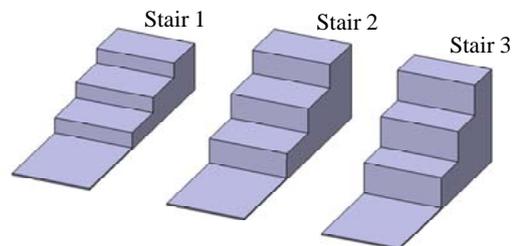


Fig. 5 Three types of stairs of user condition

TABLE I
 USER CONDITION OF STAIRS

| Parameters | Values | | |
|----------------|---------|---------|---------|
| | Stair 1 | Stair 2 | Stair 3 |
| Width (mm) | 300 | 310 | 240 |
| Height (mm) | 100 | 160 | 200 |
| Slope (degree) | 18.4 | 27.3 | 39.8 |

IV. OPTIMAL DESIGN PROCESS AND RESULT

A. Taguchi Method

Taguchi method is the way of drawing robust design parameters by using experiments or simulations when there are various user conditions [10]. It is effective way when draw an objective function just did experiment or when there are various user conditions or when arithmetical calculation of objective function was difficult. The process of Taguchi methodology can be sum up as follows.

- Define of the optimization problems: Design parameters, Objective function, User conditions.
- Experiment design using orthogonal array and linear graph.
- Analysis of sensitivity using Signal to Noise (S/N) ratio.
- Repeated performance until getting the optimal values.

We can draw robust design parameters that present stable performance through process above when there are various user conditions.

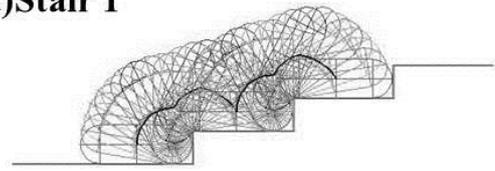
B. Interim Findings of Optimal Design

We select the orthogonal matrix for optimization process. So, we use $L_9(3^4)$ cause optimization of three design parameters [10]. In the tree types of design parameters, ω_h can be assumed as the parameter that according to conditions. Therefore, we draw the optimal value as fallow process.

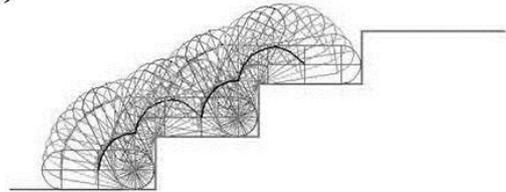
- Set the ω_h that enables climbing stairs continuously. In order words, select the ω_h that allows keeping the initial condition among the repetitive climbing stairs.
- We draw the robust optimal value of two design parameters by Taguchi methodology about three types of stairs.

We conduct the optimization through process above. Table II shows the design of experiment and result on $L_9(3^4)$ orthogonal matrix.

a)Stair 1



b)Stair 2



c)Stair 3

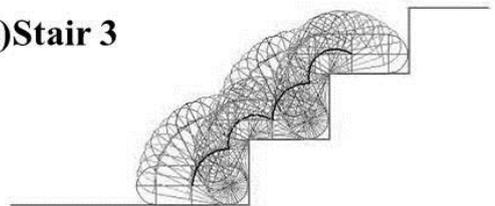


Fig. 6 Photo of simulation by using AutoCAD
 a) Stair 1, b) Stair 2, and c) Stair 3 when $l_p = 340$ mm and $h_p = 120$ mm

TABLE II
 SIMULATION PLAN AND RESULTS OF 1ST STAGE OPTIMIZATION BASED ON L9 (34) ORTHOGONAL ARRAY

| Simulation number | Design parameters Value (level) | | | | | Noise Factors | | | SN ratio (dB) |
|-------------------|---------------------------------|------------|--------------------|--------|--------|---------------|----------|----------|---------------|
| | l_p (mm) | h_p (mm) | ω_h (rad/s) | | | Stair 1 | Stair 2 | Stair 3 | |
| | | | Stair1 | Stair2 | Stair3 | | | | |
| 1 | 310 (1) | 100 (1) | 7.87 | 4.76 | 3.71 | 23022.26 | 22064.53 | 11530.63 | -85.84 |
| 2 | 310 (1) | 120 (2) | 8.41 | 5.56 | 3.71 | 22890.34 | 21043.54 | 11796.46 | -85.67 |
| 3 | 310 (1) | 140 (3) | 8.96 | 6.46 | 3.71 | 22677.83 | 19709.74 | 12649.23 | -85.49 |
| 4 | 340 (2) | 100 (1) | 5.83 | 3.06 | 2.86 | 22612.54 | 23337.57 | 11121.84 | -85.95 |
| 5 | 340 (2) | 120 (2) | 6.73 | 3.98 | 2.86 | 22752.21 | 22486.15 | 11582.58 | -85.86 |
| 6 | 340 (2) | 140 (3) | 7.49 | 4.84 | 2.86 | 22580.22 | 21329.68 | 11196.95 | -85.60 |
| 7 | 370 (3) | 100 (1) | 4.00 | 1.00 | 2.00 | 21905.12 | 23080.52 | 11180.5 | -85.79 |
| 8 | 370 (3) | 120 (2) | 4.00 | 1.00 | 2.00 | 21225.50 | 21778.92 | 10985.39 | -85.42 |
| 9 | 370 (3) | 140 (3) | 4.00 | 1.00 | 2.00 | 20747.87 | 20693.65 | 10899.07 | -85.13 |

We set $l_p = 340\text{mm}$ and $h_p = 120\text{mm}$ as initial value based design possibility. And set $l_p = 30\text{mm}$ and $h_p = 20\text{mm}$ as level difference. We performed the AutoCAD which is Computer Aided Design (CAD) program used commonly for calculate kinematic result value. Fig. 6 shows the example of simulation using AutoCAD.

We know stair climbing continuously can be possible by controlling ω_h , and it is calculated assuming it spends 1 second to climb 1step, and the result is written Table II. The result of final simulation was analyzed as smaller-the-better S/N ratio in function (2).

$$SN = -10 \log \frac{1}{3} \sum_{i=1}^3 J_i^2 \quad (2)$$

Result of simulation and calculation result of S/N ratio were showing right of Table II. The analysis result of sensitivity using smaller-the-better S/N ratio is showed Fig. 7. Consequently, analysis result shows all the two design parameters were optimization at level 3 and sensitivity were similar. In case of length, initial value shows minimum value, S/N ratio was increase as height level increase.

Additional optimization was designed and conducted based optimal value of selected 1st optimal design.

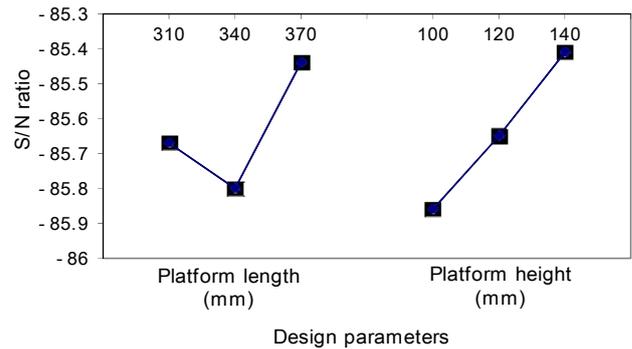


Fig. 7 Sensitivity analysis of the 1st stage

C. Result of Final Optimal Design

We conducted 2nd optimal design based optimal design based on optimal design parameters presented section above. Result shows Table III and Fig. 8.

We draw the optimal design parameters that has increased S/N ratio by optimization two steps and it is shows Fig. 8. We finished the optimization process with the two step of experiment science sensitivity analysis was collected optimal value. ω_h is the value that can be controlled according to the shape of each stairs, as mentioned earlier in section 4.2.

So, we select the ω_h 's value possibility that repetitive climbing stairs about each level and stair's type. Selected ω_h is shown to the middle of Table III.

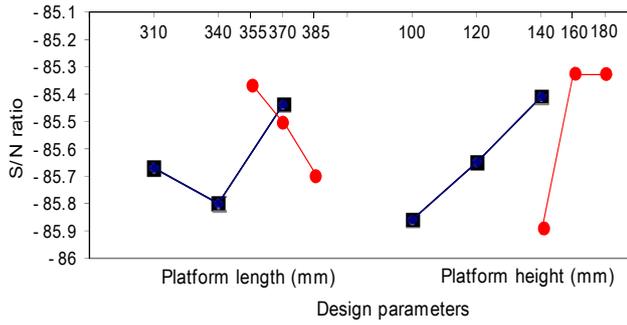


Fig. 8 Sensitivity analysis of the 1st and 2nd stages
 blue: 1st stage, red: 2nd stage

TABLE III
 SIMULATION PLAN AND RESULTS OF 2ND STAGE OPTIMIZATION BASED ON $L_9(3^4)$ ORTHOGONAL ARRAY

| Simulation number | Design parameters Value (level) | | | | | Noise Factors | | | SN ratio (dB) |
|-------------------|---------------------------------|------------|--------------------|--------|--------|---------------|---------|---------|---------------|
| | l_p (mm) | h_p (mm) | ω_h (rad/s) | | | Stair 1 | Stair 2 | Stair 3 | |
| | | | Stair1 | Stair2 | Stair3 | | | | |
| 1 | 355 (1) | 140 (1) | 4.57 | 3.77 | 2.43 | 22474.8 | 21766.6 | 11122.2 | -85.653 |
| 2 | 355 (1) | 150 (2) | 4.67 | 3.77 | 2.27 | 22427.9 | 21107.9 | 10965.3 | -85.518 |
| 3 | 355 (1) | 160 (3) | 2.88 | 1.13 | 2.13 | 21273.2 | 19085.7 | 11199.6 | -84.970 |
| 4 | 370 (2) | 140 (1) | 2.86 | 0.86 | 2.00 | 21524 | 21537 | 10788.6 | -85.414 |
| 5 | 370 (2) | 150 (2) | 2.67 | 2.13 | 1.87 | 20412.5 | 21004.1 | 10750.6 | -85.112 |
| 6 | 370 (2) | 160 (3) | 3.79 | 3.29 | 1.75 | 23220.3 | 22161.8 | 10760.5 | -85.821 |
| 7 | 385 (3) | 140 (1) | 2.43 | 0.43 | 1.57 | 27908.1 | 22084.3 | 10648.6 | -86.627 |
| 8 | 385 (3) | 150 (2) | 2.27 | 0.40 | 1.47 | 21179.2 | 21493.2 | 10563.6 | -85.324 |
| 9 | 385 (3) | 160 (3) | 2.13 | 0.38 | 1.38 | 20911.8 | 20922.6 | 10479.2 | -85.163 |

V. ANALYSIS RESULT OF OPTIMAL DESIGN

Table IV shows the initial design values and final design parameter values. In conclusion, we confirm the increase of performance about 0.89dB (22.7%) by simulation of using two times of orthogonal matrix and controlling the value of ω_h . Fig. 9 shows the result of simulation that climbs the three types of stairs about initial value and optimal value, and we confirm that difference of trace error at each design parameter.

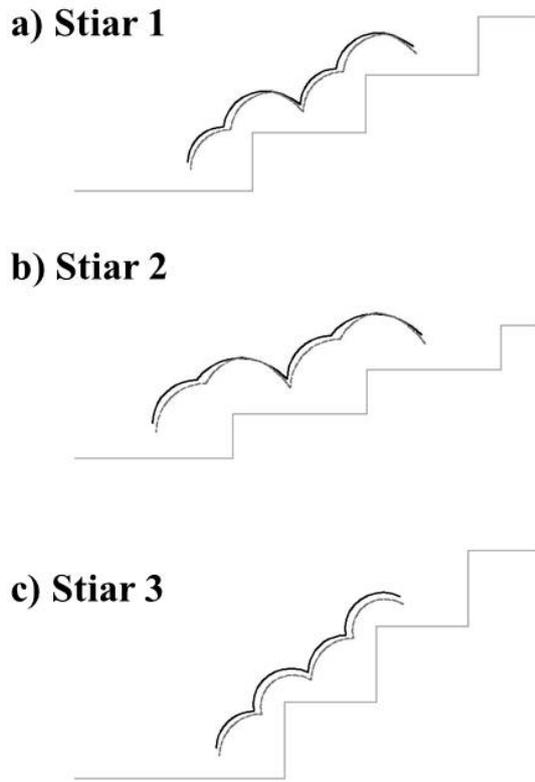


Fig. 9 Comparison between initial and optimized design parameters for climbing stairs
 Solid bold line denotes the optimized path and dashed gray line denotes the initial path

Finally, we draw the minimum design parameters that have less change of center of mass in various stairs. Also, this design parameters can be defined as the kinematic parameters which optimize the stability of stair climbing. We control and treat ω_h according to the parameters of each shape of stairs as showing Table IV.

TABLE IV
 INITIAL DESIGN PARAMETERS AND OPTIMAL DESIGN PARAMETERS

| Parameters (units) | Values | |
|--------------------|---------|---------|
| | Initial | Optimal |
| l_p (mm) | 340 | 355 |
| h_p (mm) | 120 | 160 |
| ω_h (rad/s) | Stair1 | 6.73 |
| | Stair2 | 3.98 |
| | Stair3 | 2.86 |
| SN ratio (dB) | -85.86 | -84.97 |

VI. CONCLUSION

This research conducted the optimization of the kinematic parameters for new concept of robot platform which does body flip locomotion. We did optimization with two parameters of geometrical length and parameters of angular velocity. We selected the three types of shaped stairs as user condition of robot, and draw the robust optimal value by kinematic

simulation based on the user condition. Finally, we improved its performance as 0.89dB (22.7%) by minimize of pitching of center of mass. Additionally we calculate angular velocity as variable according to various user conditions. We are producing robot platform using the optimal design parameters as continuous research of this paper. It will improve the reliability of this research through production and doing experiment about prototype. We will research on optimal control that reduces the required energy and autonomous control used sensor about new robot platform. This robot platform will be used as a base robot platform as work of prevention of fire, detection of radioactivity leak.

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