IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received November 11, 2019, accepted November 24, 2019, date of publication November 27, 2019, date of current version December 13, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2956163

Curved-Spoke Tri-Wheel Mechanism for Fast Stair-Climbing

YOUNGSOO KIM[1], JONGWON KIM[1], HWA SOO KIM[2], (Member, IEEE), AND TAEWON SEO[3], (Member, IEEE)
[1]School of Mechanical and Aerospace Engineering, Seoul National University, Seoul 151-744, South Korea
[2]Department of Mechanical System Engineering, Kyonggi University, Suwon-si 443-760, South Korea
[3]School of Mechanical Engineering, Hanyang University, Seoul 04763, South Korea

Corresponding authors: Hwa Soo Kim (hskim94@kgu.ac.kr) and Taewon Seo (taewonseo@hanyang.ac.kr)

This work was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF) grant funded by the Ministry of Science and ICT under Grant NRF-2019R1A2C1008163.

ABSTRACT Stairs are common obstacles in indoor environments and are difficult to overcome for robots. The speed of robot stair-climbing should be similar to that of humans for commercial products, but their speed remains limited. Additionally, the variety of dimensions of stairs is also a significant problem for robust stair-climbing by robots. In this paper, a curved spoke-based tri-wheel mechanism is proposed for fast and robust stair-climbing. The goal speed of stair-climbing is similar to the human speed for variously sized stairs. The proposed wheel system is composed of a tri-wheel mechanism with a curved spoke, wherein the dimensions of the mechanism are determined based on a kinematic analysis. Between the tri-wheels, a stopper mechanism acts to make the initial condition of the sequential stair-climbing the same as the initial starting condition. Static analysis to analyze the minimum friction coefficient is performed to verify the performance of the robot. Experiments based on the prototype are performed to verify the stair-climbing speed for variously sized stairs; the results indicate that fast and robust stair climbing performance is achieved. These findings can be used to design an indoor service robot for various applications.

INDEX TERMS Stair-climbing, tri-wheel, indoor service robot, kinematic design, friction coefficient.

I. INTRODUCTION

Stairs are common and difficult obstacles for robots in indoor environments. To create a working indoor service robot, stair-climbing capabilities are necessary. The speed and stability of stair-climbing should be high enough to allow the robot to perform indoor service. Additionally, the robustness of stair-climbing is important, as there are many different shapes, materials, and dimensions of stairs.

Dexterous bipedal and quadrupedal robots might be the best solution for indoor service. Recently, Boston dynamics showed that the SpotMini can climb up and down stairs with fast and stable motion [1]. At the DARPA robotics challenge, several robots also successfully performed stair-climbing even though their performance was not sufficiently fast and robust [2], [3]. A legged robot design has good advantages, in that the robot can be the optimal solution for artificially designed structures for human beings; however, the mechanism and control are quite complicated, and more research is required before such robots can be commercialized.

Relatively simple mechanisms, as compared to legged robots, are proposed for stair-climbing. Table 1 summarizes several of the proposed mechanical solutions for stair-climbing. Tracked robots, which have simple design and control, are the most popular solution [4]. Seo et al. modified a tracked robot to add a flipping motion for effective stair-climbing [5]. Wheel-linkage mechanisms, such as the rocker-bogie mechanism [6] used in Mars exploration, have been proposed by researchers for climbing stairs [7]–[9]. RHex [10], with curved legs developed for unstructured environments, has also been used for stair climbing. Modified wheel mechanisms, such as the tri-wheel, have been found to realize effective stair climbing [11]. Several studies have focused on these systems; however, the systems involve several drawbacks, such as friction problems because of edge contact (tracked), complicated design (wheel-linkage), the need for a high degree-of-freedom (DOF) (wheel-linkage and curved wheel), and poor adaptation to different stair sizes (modified wheel). Based on these drawbacks,

The associate editor coordinating the review of this manuscript and approving it for publication was Xiwang Dong.

TABLE 1. Comparison of various stair-climbing robots.

Mechanism	Tracked	Flipped track	Wheel-linkage	Curved legs	Modified wheel	Curved-spoke tri-wheel
Picture						
Name	Packbot [4]	FlipBot [5]	RHyMo [7]	RHex [10]	Loper [11]	*This research*
Climbing speed	1 step/s	1 step/s	0.5 step/s	0.5 step/s	2 step/s	3 step/s (40 m/min)
Operation stability	–	–	+	+	+	+
Design complexity	+	+	–	–	+	+
Adaptation to stair size	+	+	+	–	–	+
Limitation	- Edge contact	- Flipping motion	- Complicated structure - High-DOF	- Discrete motion - High-DOF	- Adaptation to different stair-size - Flat surface operation	- Flat surface operation

the performance in terms of stair-climbing speed, stability, and robustness is not satisfactory.

In order to climb different sizes of steps effectively, many investigations have been conducted. For example, the track mechanism has been combined with the wheel mechanism [12] and additional active actuators have been added to the wheel mechanism [13]. Furthermore, various transformable wheels have been recently suggested. In [14], the wheel can be changed into leg by simply folding it and multiple wheels have been combined to act as a leg [15]. Chocoteco et al. developed a stair-climbing wheel-chair platform by using a four wheels equipped on symmetric four-bar mechanism and achieve stable and comfortable stair-climbing [16] It is noted that since these existing mechanisms have focused on climbing stairs, the resulting mobile stabilities during their climbing have not been considered as an important factor. Also, the climbing speed is quite limited and the speed should be improved to widen the application area.

This paper proposes a new robot mechanism for fast and robust stair-climbing. Using a curved spoke-based tri-wheel mechanism, the robot can perform stair-climbing faster than a human can. Additionally, by applying a stopper mechanism, the robot can adapt to various sized stairs. Kinematic and static analyses are performed to guarantee high stair climbing performance. The experimental results fully validate the proposed concept.

This study involves the performance of two analyses: kinematic and static. There are two performance indices for each analysis, which are well-known indices in stair-climbing robot's evaluation. First, for kinematic analysis, we used the deviation of center of rotation (CoR) position during stair climbing [17]. This index defines the stability of the stair-climbing by minimizing the vertical directional acceleration and backward velocity. If the CoR line is a straight line during stair climbing, the index indicates perfect stair climbing. The second index is the minimum required friction coefficient during stair-climbing [18]. This index can be derived from the static analysis. A lower friction coefficient denotes that the stair-climbing is more stable. If a robot guarantees low minimum coefficient of friction, the robot can climb various stairs with different materials which are smooth and rough. Also, with low minimum coefficient of friction, the robot has large stability margin and the robot can climb relatively rough surface easily. Based on these analyses, the design parameters can be determined optimally.

Curved-spoke design has been researched by many researchers to overcome unstructured environments such as stairs. The most popular case is RHex [7] design achieving tripod gait with six compliant half-circular spokes. There are similarity in the design of the proposed mechanism with other curved-spoke design; however, this research has contribution that (1) two curved-spoke tri-wheel is proposed for stair-climbing, (2) optimal design with kinematic and static analyses are performed, and (3) stopping mechanism is proposed for high repeatable stair-climbing. As results of the proposed mechanism, the robot can achieve high-speed climbing of 3 step/s, as shown in Table 1, with sequential stepping with high repeatability. This performance guarantees the robot can climb long stairs in a short time, which is not an easy mission for other robotic platforms.

The remainder of this paper is organized as follows. Section 2 describes the design of the mechanism of the proposed robot. Sections 3 and 4 present the kinematic and static analyses of stair-climbing. The design parameters are determined based on the analysis results. Section 5 presents the prototype assembly experimental results, and the experimental results for various sized stairs. The climbing speed is the main performance metric to be analyzed. Concluding remarks address future work in Section 6.

II. MECHANISM DESCRIPTION

Figure 1(a) shows the proposed stair-climbing robot mechanism. The robot is composed of a main body with a controller, a tail with a rear wheel, and two curved-spoke-based tri-wheel assemblies with motors. A tail part was used to maintain 3-point support and wheels are used to minimize resistance of rear contact during driving. Only two motors are used to operate the robot, both to climb stairs and to steer. Using the curved-spoke assembly, the robot can climb stairs.

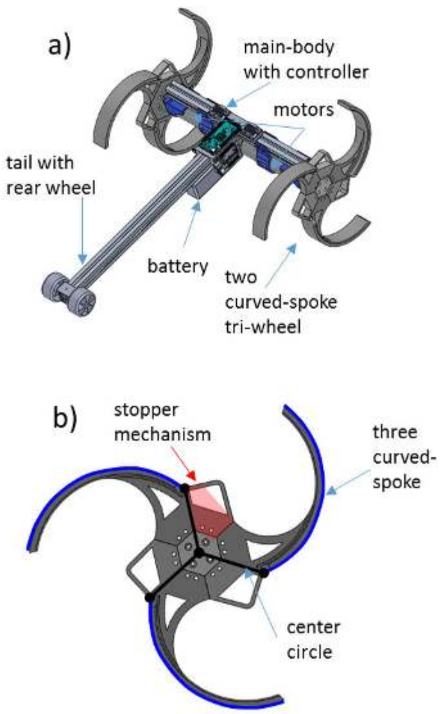

FIGURE 1. Mechanism configuration of the proposed curved-spoke-based tri-wheel mechanism. (a) Overall configuration, and (b) curved-spoke wheel mechanism.

The curved-spoke-based tri-wheel mechanism is shown in Fig. 1(b). The kinematic parameters, radius of center circle, radius of the curved spokes, and the angle between the radius of the center circle and the spoke should be optimized to allow the robot to climb stairs well. Kinematic and static analyses are required to determine the kinematic parameters, as explained in Sections 3 and 4.

The stopper mechanism in Fig. 1(b) is designed to solve the problem of slipping on sequential steps on stairs. As shown in Fig. 2, there should be variance in the slipping distance during sequential stepping, and the distance should be accumulated while stair-climbing. This phenomenon makes the analysis difficult and prevents the robot from climbing stairs continuously. The stopper mechanism makes the initial conditions of sequential stepping the same as shown in Fig. 3.

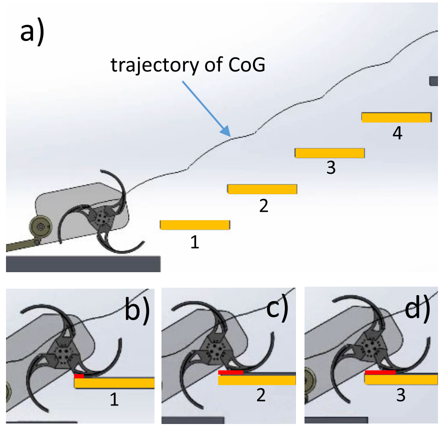

FIGURE 2. Three-curved-spoke-based stair-climbing and problem of slipping for sequential stair-climbing. (a) Sequential stair-climbing and the trajectory of the center of gravity (CoG), and (b-d) problem of slipping during stepping on the 1st to 3rd stairs. The red line shows that the slip length is increased as the robot travels up the stairs.

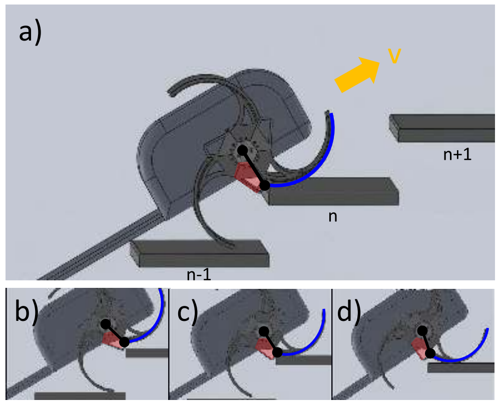

FIGURE 3. Function of the stopper mechanism. (a) n-th stair during climbing. Note there is no slip after the n-th sequential stair. (b-d) the operation of the stopper mechanism at the corner. (b) The edge of the stopper mechanism touches the riser, (c) the corner of the stopper mechanism rolls following the corner of the stair, and (d) the curved-spoke performs stair-climbing with the same initial condition.

The edge of the stopper mechanism is always in contact with the edge of the stairs. The robot can climb a stair with the same initial condition as shown in Fig. 3(a).

III. KINEMATIC ANALYSIS

To perform stable stair-climbing, the kinematic parameters should be selected carefully. In this paper, the design parameters are selected based on perfect step climbing with no slippage, and step-climbing is sequentially repeated to enable the robot to climb the stairs. Based on this assumption, the kinematic parameters can be simply determined using a system of algebraic equations

Figure 4 shows the kinematic configuration of stair-climbing. There are four independent parameters, r_1 (radius of the center circle), r_2 (radius of the curved spoke), θ_1 (angle between the radius of the center circle and the spoke), and θ_2 (angle of the curved spoke piece). Here, θ_2 is designed

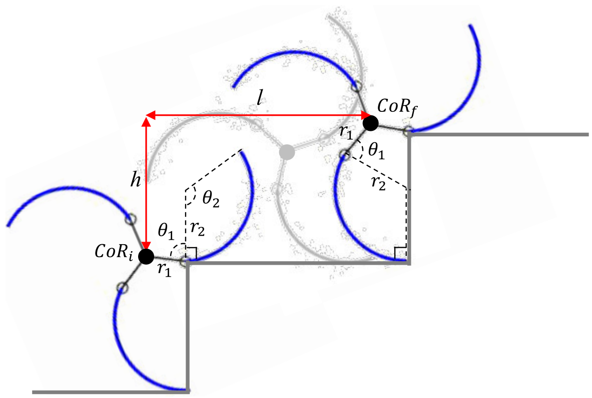

FIGURE 4. Free-body diagram for the kinematic analysis.

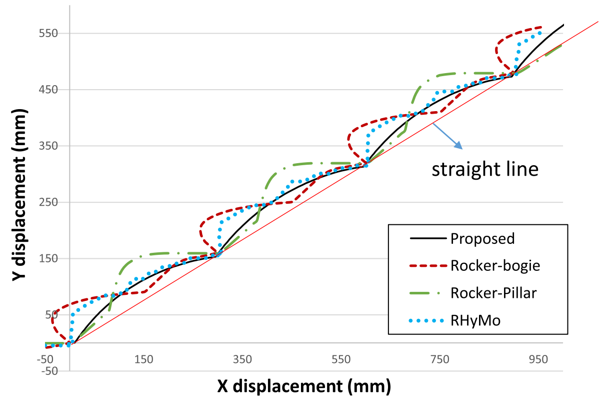

FIGURE 5. Center of mass trajectory of stair-climbing simulation results based on kinematic analysis.

to be 120°, so as to make a tri-wheel mechanism. If the movement of CoR is moved from the initial position (CoR_i) to the final position (CoR_f) in an ideal way, the length l and height h can be derived using the following algebraic equations:

$$l = r_2\left(\theta_2 - \frac{\sqrt{3}}{2}\right) + r_1\left(\sin\theta_1 - \sin(\theta_1 - \theta_2)\right), \quad (1)$$

$$h = \frac{3}{2}r_2 + r_1\left(-\cos\theta_1 + \cos\left(\theta_1 - \theta_2\right)\right). \quad (2)$$

From these relations, r_1, r_2, and θ_2 can be defined for given stair dimensions, l and h. Note that r_2 should satisfy the inequality constraint to make the rolling length less than the length of a stair:

$$\frac{2}{3}\pi r_2 < l. \quad (3)$$

To determine the kinematic parameters, r_2 is designed to be 124 mm, so as to satisfy (3) for the same stepping length when $l = 260$ mm. Based on r_2, r_1 and θ_1 are determined to be 86 mm and 50°, respectively, from (1) and (2). l and h were selected as 300 mm and 160 mm, which is the most common step size existing in human living environment.

The linearity characteristics of the selected design variables are analyzed by simulation. Three different mechanisms are selected, i.e., Rocker-bogie [19], [20], Rocker-Pillar [21] and RHyMo [7], which are specifically designed for stair-climbing. Figure 5 shows the results of the simulation. The red line is a straight line parallel to the slope of the stairs and curves show the center of the mass trajectory of each mechanism. Rocker-bogie mechanism shows a backward movement of the center of mass during stair climbing, which is undesired motion in terms of stability. Rocker-pillar is a mechanism proposed to increase the traversability during stair climbing by using the front active track. Rocker-pillar eliminated backward motion but has large fluctuations due to the rear Rocker mechanism. By applying the inverse four-bar linkage mechanism, RHyMo effectively minimizes fluctuations of center of mass and shows smooth trajectory which is close to the straight line.

The linearity of the CoR line was defined as the average and maximum value of the deviation of the vertical displacement with respect to the linear trajectory. The maximum values of the proposed curved-spoke tri-wheel, rocker-bogie, rocker-pillar and RHyMo were 24.1 mm, 28.4 mm, 33.9 mm and 26.2 mm, respectively, and the maximum values were 37.8 mm, 70.4 mm, 78.4 mm and 51.1 mm, respectively. The proposed curved-spoke tri-wheel robot showed the smallest average value and the maximum value. In particular, the maximum value shows a significant difference. The maximum instantaneous value is important for the stability of the robot in overcoming the stairs, which is a meaningful result.

As a result, the proposed curved-spoke tri-wheel mechanism shows the best linearity of CoR line, as compared to other mechanisms. Based on the simulation results, the design guarantee stable stair-climbing.

IV. STATIC ANALYSIS OF FRICTION COEFFICIENT

The friction between the wheel and the stair is particularly important for performing stable stair-climbing. It is important to reduce the maximum required friction coefficient because it is directly connected with the ability to overcome obstacles. If the actual friction coefficient value is smaller than the required friction coefficient value, slip occurs and the obstacle cannot be overcome. To maximize the stair climbing ability, while minimizing the required coefficient of friction structurally, wheel materials with sufficiently high friction coefficient should be used to fabricate the wheels. The minimum required friction coefficient is widely used to evaluate the stability of stair-climbing [8].

Static analysis is performed based on the free-body diagram shown in Fig. 6. l_{bf}, l_r, d_b, and h_b are the length from the front to the CoR, length from the front to the contact point of the main body, height of the CoR relative to the bottom, and height from the contact point to the CoR of the main body, respectively. x_c and y_c are the distance between the spoke's contact point and the CoR during stepping. m is the mass of the main body. μ_1 and μ_2 are the friction coefficients of the main body and tri-wheel mechanism, respectively. N_r and N_w

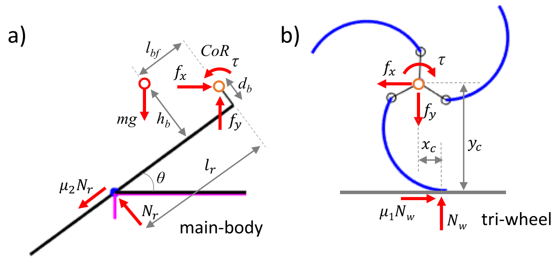

FIGURE 6. **Free-body diagram for static analysis: (a) main body and (b) tri-wheel mechanism.**

are the normal forces in the main-body contact point and the wheel contact point, respectively. f_x, f_y, and τ denote the reaction forces and torque at the CoR, respectively.

The force and moment equilibrium equations for the main body ((4)–(6)) and tri-wheel mechanism ((7)–(9)) are as follows:

$$\Sigma F_x = -\mu_2 N_r \cos\theta - N_r \sin\theta + f_x = 0, \quad (4)$$

$$\Sigma F_y = -mg - \mu_2 N_r \sin\theta + N_r \cos\theta + f_y = 0, \quad (5)$$

$$\Sigma M_{CoR} = mg\,(h_b - d_b)\sin\theta + mgl_{bf}\cos\theta - N_r l_r - \mu_2 N_r d_b + \tau = 0, \quad (6)$$

$$\Sigma F_x = \mu_1 N_w - f_x = 0, \quad (7)$$

$$\Sigma F_y = -N_w + f_y = 0, \quad (8)$$

$$\Sigma M_{CoR} = -N_w x_c - \mu_1 N_w y_c + \tau = 0. \quad (9)$$

where N_r, N_w, f_x, f_y, and τ are unknown forces, and μ_1 and μ_2 are undefined parameters, which are expected to be geometrical parameters. Because μ_2 should be minimized for better step-climbing, μ_2 is set to be 0.1 for the robot. Then, the six unknown parameters can be determined using (4)–(9).

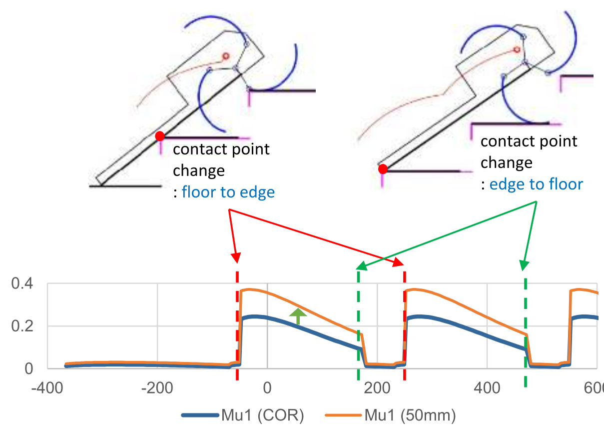

FIGURE 7. **Required minimum friction coefficient μ_1 during climbing of a 300 × 160 mm^2 stair. The blue line is when the CoR and CoG are in the same vertical line, and the red line is when the CoR and CoG have a horizontal distance of 50 mm.**

The simulated minimum required μ_1 value is shown in Fig. 7. The same kinematic parameters are used as in Section 3; the other values of (4)–(9) are set as follows: $(l_{bf}, L, d_b, h_b) = (50, 600, 30, 80)$ mm. The mass m is set to be 6 kg by considering the prototype model. As shown in Fig. 7, the required value of μ_1 is increased when the contact point is changed from the floor to the edge and is decreased when the contact point is changed from the edge to the floor, which indicates that the edge contact is insufficient, in terms of required friction coefficient. It is important to note the μ_1 is independent to the mass when the CoR and center of gravity (CoG) is coincident, which is very good characteristics to increase the payloads. The value of required friction coefficient is changed as the CoR and CoG become mismatched, as shown in Fig. 7 (wherein a red line indicates the CoG, which has a horizontal offset of 50 mm from the CoR). To design a high-performance robot, the CoG should be coincident with the CoR so as to guarantee a low required friction coefficient.

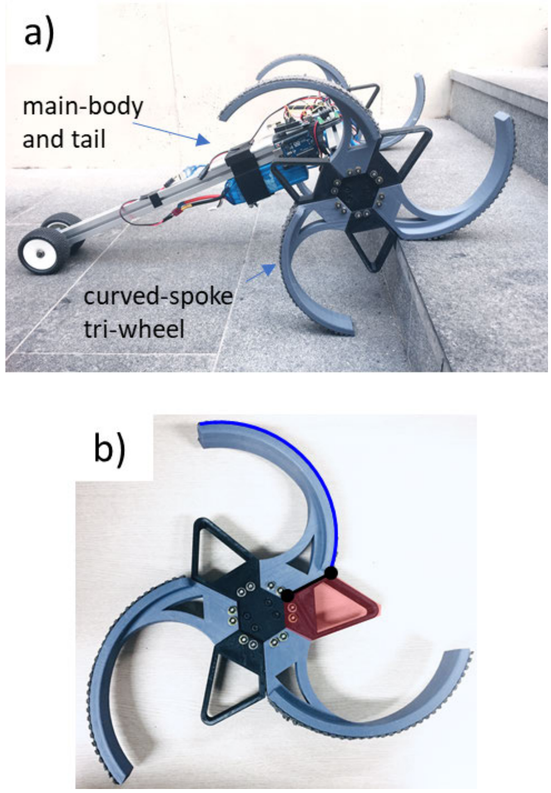

FIGURE 8. **Assembled prototype: (a) overall shape on a stair and (b) the curved-spoke tri-wheel mechanism.**

The maximum required friction coefficient of the other robotic solutions can be a reference for evaluating the required friction coefficient of the proposed mechanism. The length of the robot and the size of the wheel is set 600 mm and 250 mm respectively. The value of the maximum required friction coefficient when the rocker-bogie platform overcomes the stairs is as high as 2.1[14]. The robots of the wheel-link structure depend on the frictional force of the wheel in the process of overcoming obstacles, so the value of the required friction coefficient is high. The RHyMo platform has an inverse four-bar mechanism that distributes the load evenly

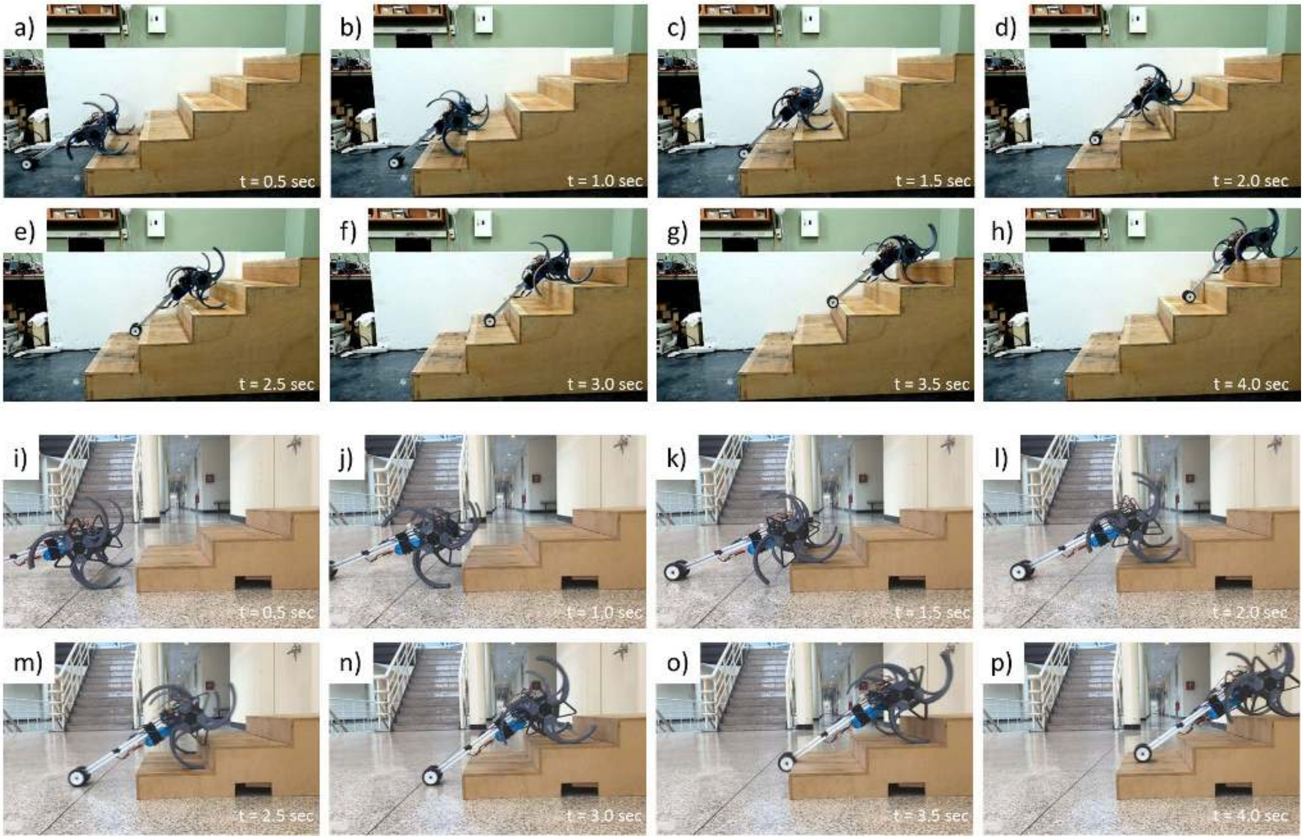

FIGURE 9. Stair-climbing experimental results with stair dimensions of (a–h) 300 × 160 mm2 and (i–p) 300 × 100 mm2. See the Multimedia supplement for a detailed explanation of the stair-climbing sequence.

across the wheel, effectively reducing the required friction coefficient when overcoming obstacles to 0.44 [7].

The results show that the proposed robot required relatively little friction coefficient to perform stair-climbing. The maximum required friction coefficient is 0.22. It is half the value compared to the RHyMo platform. This is possible because the proposed robot maintains only bottom and edge contact in the obstacle overcoming process. By eliminating contact with the vertical plane, it is possible to avoid the situation where the load of the robot should be supported by the frictional forces. Also, it is important to note the reduction of mass by mechanical simplicity helps to reduce the required minimum coefficient. In the next section, the verification of the effectiveness is described for the proposed design using experiments.

V. EXPERIMENTAL RESULTS

The prototype was assembled as shown in Fig. 8. The fabricated dimension of the curved-spoke wheel mechanism was based on the results of the analysis ($r_1 = 86$ mm, $r_2 = 124$ mm, $\theta_1 = 50°$). The size of the prototype is 500 (width) ×600 (length) mm^2 and the weight is 6 kg. Two DC-geared motors (52GM, 1:53 gear ratio, 48.6 W) are used with a battery. Arduino Uno is used for the controller with a DC-motor driver. and DC drivers (NT-DC20A, NTREX, Korea, AM-DC1-3D, NEWTC, Korea) were used for motor control. Arduino Mega (Italy) and Wii wireless classic controllers (Nintendo, Japan) are used to control the prototype. The main body and tail are made of aluminum. The curved spoke with a stopper mechanism is made using a 3D printer and ABS material.

The prototype was tested on two stairs of different sizes, 300 × 160 mm^2 and 300 × 100 mm^2, as shown in Fig. 9 (a–h) and (i–p), respectively. Please refer to the detailed diagram of step-climbing in the Multimedia supplement. The speed is varied from 5 m/min to 40 m/min (3 step/s), which is a higher speed than that of typical human stair-climbing. The results showed that the robot can stably climb the stairs at high speed via repeated motion. As shown in Fig. 10(a–b), the stopper mechanism causes the initial condition for each new step to be the same; the curved spoke is used to walk on the stairs stably. The mechanism works well on different sizes of stairs. Without the stopper mechanism, the slip length is changed, as shown in Fig. 10(c–d), which shows the stepping posture for first and second steps without the stopper. As the length of the stopper mechanism increases, the range of applicable step sizes increases. Therefore, the stopper mechanism of an appropriate size suitable for the environment in which the robot is used may be selected.

As shown in Fig. 11(a-d), field test was also performed on stairs with dimensions of 300 × 160 mm^2 with size deviations of 10 mm to check the practicality of the mechanism.

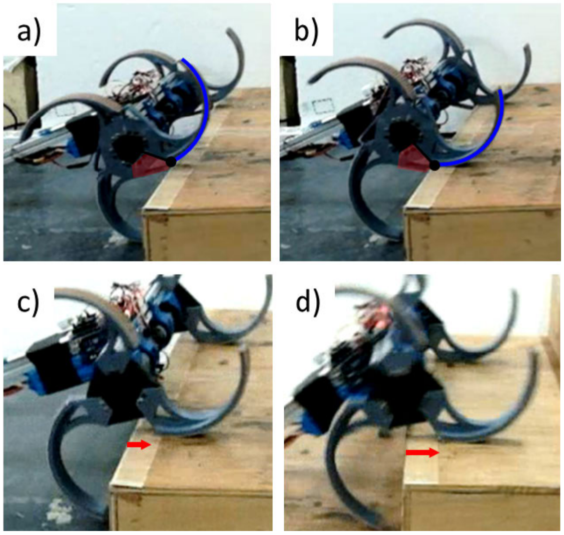

FIGURE 10. Function of the stopper mechanism during stair-climbing: (a) when the stopper mechanism makes contact with the edge of a step, and (b) the curved-spoke walks on the step. Without the stopper mechanism, the slip length is increased between the (c) first step and the (d) second step.

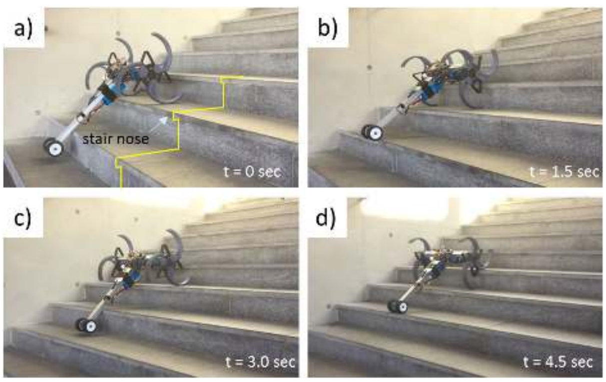

FIGURE 11. Stair climbing field test with stair dimensions of 300 × 160 mm2 with size deviations of 10 mm. See the Multimedia supplement for a detailed explanation of the stair-climbing sequence.

For stairs in real life, not only size deviations but low friction condition also exists compared to experimental environment. It also went up well despite the stairs with the nose as shown in Fig. 11(a). Wheel linkage mechanism robot is unable to overcome stairs with nose or stairs without riser, but our proposed curved wheel robot can overcome various types of stairs even when the friction coefficient is low. Please refer to the detailed postures of step-climbing in the Multimedia supplement.

Using high-power motor can be helpful to increase the climbing speed. However, the configuration should be optimized since increasing motor power can increase the weights, as we analyzed in Section IV. Also, the minimum required friction should be analyzed carefully to prevent slipping during climbing in high speed rotation of the spoke. In this research, the motor power is not optimized analytically, but the parameters are determined based on the experiences.

VI. CONCLUSION

This paper presented a robot design for stair-climbing using a curved-spoke tri-wheel mechanism. Using the mechanism, the robot can climb stairs at a high speed. The robot can climb stairs with stair noses on the stairs, or stairs without risers. The stopper mechanism has a key role in making the initial condition of sequential stair stepping the same for each step. Based on kinematic and static analyses, the design parameters were determined such that the CoR followed a straight line and the required friction coefficient was small. After manufacturing the prototype, the stair-climbing performance was successfully verified by experiments and field tests.

To use the robot as an indoor service robotic platform, the moving performance of flat ground should be improved. Descending performance should be improved to minimize the slippery and impact during the locomotion, which can be achieved by inversely rotating the curved-spokes. We are planning to extend the curved-spoke tri-wheel mechanism idea to a shape-morphing wheel design. By changing the tri-wheel to a circular normal wheel based on a transformation mechanism based on a parallel linakge, stable and high-speed locomotion on both flat ground and stairs are going to be achieved. The analysis and experimental results are going to be shared in the next publication shortly.

REFERENCES

[1] *SpotMini Autonomous Navigation*. Accessed: Nov. 6, 2018. [Online]. Available: https://www.youtube.com/watch?v=Ve9kWX_KXus

[2] T. Jung, J. Lim, H. Bae, K. K. Lee, H.-M. Joe, and J.-H. Oh, "Development of the humanoid disaster response platform DRC-HUBO+," *IEEE Trans. Robot.*, vol. 34, no. 1, pp. 1–17, Feb. 2018.

[3] M. Zucker, S. Joo, M. X. Grey, C. Rasmussen, E. Huang, M. Stilman, and A. Bobick, "A general-purpose system for teleoperation of the DRC-HUBO humanoid robot," *J. Field Robot.*, vol. 32, no. 3, pp. 336–351, 2015.

[4] B. M. Yamauchi, "PackBot: A versatile platform for military robotics," *Proc. SPIE*, vol. 5422, pp. 228–237, Sep. 2004.

[5] B. Seo, H. Kim, M. Kim, K. Jeong, and T. Seo, "FlipBot: A new field robotic platform for fast stair climbing," *Int. J. Precis. Eng. Manuf.*, vol. 14, no. 11, pp. 1909–1914, 2013.

[6] R. A. Lindemann and C. J. Voorhees, "Mars exploration rover mobility assembly design, test and performance," in *Proc. IEEE Int. Conf. Syst., Man Cybern.*, Waikoloa, HI, USA, Oct. 2005, pp. 450–455.

[7] D. Choi, Y. Kim, S. Jung, J. Kim, and H. S. Kim, "A new mobile platform (RHyMo) for smooth movement on rugged terrain," *IEEE/ASME Trans. Mechatronics*, vol. 21, no. 3, pp. 1303–1314, Jun. 2016.

[8] R. Siegwart, P. Lamon, T. Estier, M. Lauria, and R. Piguet, "Innovative design for wheeled locomotion in rough Terrain," *Robot. Auton. Syst.*, vol. 40, nos. 2–3, pp. 151–162, 2002.

[9] T. Thueer, P. Lamon, A. Krebs, and R. Siegwart, "CRAB—Exploration rover with advanced obstacle negotiation capabilities," in *Proc. 9th ESA*, 2006, p. 2.

[10] E. Z. Moore, D. Campbell, F. Grimminger, and M. Buehler, "Reliable stair climbing in the simple hexapod 'RHex,'" in *Proc. IEEE Int. Conf. Robot. Autom.*, Washington, DC, USA, May 2002, pp. 2222–2227.

[11] S. D. Herbert, A. Drenner, and N. Papanikolopoulos, "Loper: A quadruped-hybrid stair climbing robot," in *Proc. IEEE Int. Conf. Robot. Autom.*, Pasadena, CA, USA, May 2008, pp. 799–804.

[12] X. Gao, D. Cui, W. Guo, Y. Mu, and B. Li, "Dynamics and stability analysis on stairs climbing of wheel–track mobile robot," *Int. J. Adv. Robot. Syst.*, vol. 14, no. 4, pp. 1–13, 2017.

[13] G. Quaglia, W. Franco, and M. Nisi, "Kinematic analysis of an electric stairclimbing wheelchair," *Ingenieria Universidad*, vol. 21, no. 1, pp. 27–48, 2016.

[14] S.-C. Chen, K. J. Huang, C.-H. Li, and P.-C. Lin, "Trajectory planning for stair climbing in the leg-wheel hybrid mobile robot quattroped," in *Proc. IEEE Int. Conf. Robot. Automat.*, Shanghai, China, May 2011, pp. 1229–1234.

[15] A. M. M. Thu, M. T. S. Aung, and T. Okada, "Autonomous stairs ascending and descending algorithm for tri-star wheeled robot," in *Proc. 3rd Int. Conf. Adv. Robot. Mechatronics*, Jul. 2018, pp. 328–333.

[16] J. Chocoteco, R. Morales, and V. Feliu, "Improving the climbing/descent performance of stair-climbing mobility systems confronting architectural barriers with geometric disturbances," *Mechatronics*, vol. 30, no. 1, pp. 11–26, 2015.

[17] H. S. Hong, T. Seo, D. Kim, S. Kim, and J. Kim, "Optimal design of hand-carrying rocker-bogie mechanism for stair climbing," *J. Mech. Sci. Technol.*, vol. 27, no. 1, pp. 125–132, 2013.

[18] T. Thueer and R. Siegwart, "Mobility evaluation of wheeled all-Terrain robots," *Robot. Auto. Syst.*, vol. 58, no. 5, pp. 508–519, May 2010.

[19] 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 Mach. Theory*, vol. 50, pp. 90–108, Apr. 2012.

[20] H. Hong, D. Kim, H. S. Kim, S. Lee, and J. Kim, "Contact angle estimation and composite locomotive strategy of a stair-climbing mobile platform," *Robot. Comput.-Integr. Manuf.*, vol. 29, no. 5, pp. 367–381, 2013.

[21] D. Choi, J. R. Kim, S. Cho, S. Jung, and J. Kim, "Rocker-pillar: Design of the rough Terrain mobile robot platform with caterpillar tracks and rocker bogie mechanism," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Oct. 2012, pp. 3405–3410.

YOUNGSOO KIM received the B.S. and Ph.D. degrees in mechanical and aerospace engineering from Seoul National University, in 2013 and 2019, respectively. His research interests include service robot design, mobile mechanism design, and optimization.

JONGWON KIM received the B.S. degree in mechanical engineering from Seoul National University, South Korea, in 1978, the M.S. degree in mechanical and aerospace engineering from the Korea Advanced Institute of Science and Technology (KAIST), South Korea, in 1980, and the Ph.D. degree in mechanical engineering from the University of Wisconsin–Madison, USA, in 1987. He is currently a Professor with the School of Mechanical and Aerospace Engineering, Seoul National University. His current research interests include parallel mechanisms, Taguchi methodology, and field robots.

HWA SOO KIM (M'15) received the B.S. and Ph.D. degrees in mechanical engineering from Seoul National University, South Korea, in 2000 and 2006, respectively. From 2007 to 2008, he was a Postdoctoral Researcher with the Laboratory for Innovations in Sensing, Estimation and Control, University of Minnesota, MN, USA. He is currently an Associate Professor with the Department of Mechanical System Engineering, Kyonggi University. His current research interests include design, modeling, and control of various mobile platforms.

TAEWON SEO (M'10) received the B.S. and Ph.D. degrees from the School of Mechanical and Aerospace Engineering, Seoul National University, South Korea. He was a Postdoctoral Researcher with the Nanorobotics Laboratory, Carnegie Mellon University, a Visiting Professor with the Biomimetic Millisystems Laboratory, UC Berkeley, and an Assistant Professor with the School of Mechanical Engineering, Yeungnam University, South Korea. He is currently an Associate Professor with the School of Mechanical Engineering, Hanyang University, South Korea. His research interests include robot design, analysis, control, optimization, and planning. He received the Best Mechatronics Paper Award of the IEEE/ASME Transaction on Mechatronics, in 2014. He is currently a Technical Editor of the IEEE/ASME Transaction on Mechatronics and an Associate Editor of the IEEE Robotics and Automation Letters and *Intelligent Service Robots*.