

# Passive Torsional Compliance for Dynamic Stability Improvement of a Curved-Spoke Tri-Wheel\*

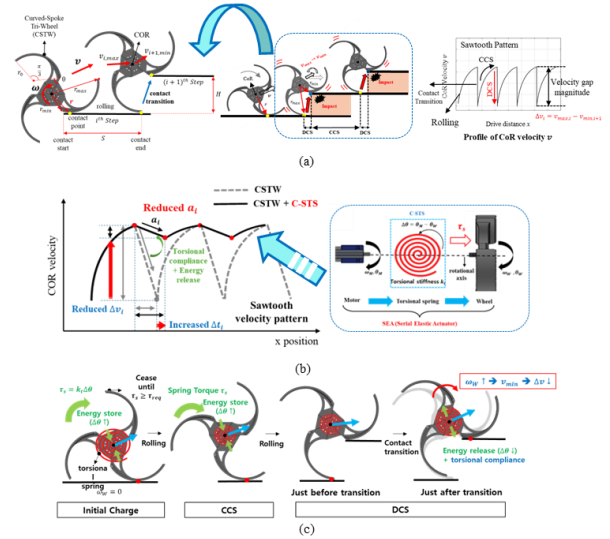
Sunbeom Jeong and Youngsoo Kim

Service robots are now being deployed in increasingly diverse environments, ranging from household support to warehouse and industrial operations. To function effectively in such settings, they must be able to move beyond flat indoor surfaces and cope with common architectural obstacles. Among these, stairs remain one of the most demanding and complex obstacles because they require both geometric adaptability and dynamic stability during repeated step-to-step transitions. Various mobile platforms have been proposed for overcoming stairs. Among them, the curved-spoke tri-wheel (CSTW) mechanism is particularly attractive because of its relatively low design complexity, while still enabling smooth and fast stair traversal using only rotational motion [1]–[4].

As shown in Fig. 1(a), the CSTW consists of three curved spokes attached to a central hub at  $120^\circ$  intervals. Due to its unique geometry, the effective rotational radius  $r$ , defined as the distance from the wheel CoR to the contact point, varies during rolling motion. The main issue arises when the wheel rotates by  $120^\circ$  and encounters the next stair. At that moment, the wheel-ground contact point shifts from one spoke to the next, referred to as a contact transition, causing the effective rotational radius to drop abruptly from its maximum to its minimum value. The transition fundamentally originates from the discontinuity in the radius of curvature between adjacent spokes. When the motor, rigidly connected to the wheel, rotates at a constant angular velocity  $\omega$ , this sudden decrease in radius leads directly to an abrupt drop in the CoR linear velocity  $v$ . The resulting velocity gap  $\Delta v$ , occurring over a very short time, can induce dynamic instability, such as impact on the payload or slip between the spoke and the stair. This gap-induced instability becomes more pronounced with increasing angular velocity or stair height, making stable and continuous climbing more difficult in typical multi-step operation.

During stair climbing, the velocity profile  $v$  of the CSTW generally exhibits a periodic sawtooth pattern consisting of two distinct phases: (1) the Continuous Contact State (CCS), where the wheel undergoes pure rolling and the velocity increases smoothly, and (2) the Discrete Contact State (DCS), where a contact transition occurs and the velocity decreases discontinuously.

\*This research was supported by the National Research Foundation (NRF) of Korea grant funded by the Korea government (MSIT) (RS-2024-00359219).



**Fig. 1.** (a) CSTW limitation caused by the discontinuity in the radius of curvature during contact transition and the resultant velocity profiles, (b) Deceleration-reduction concept of the proposed C-STs in the CSTW system, (c) Operating principles of the proposed C-STs during initial charge, CCS, and DCS.

Since the collision between the spoke and the stair nose is not impulsive, it occurs over a finite time. Thus, there exists a DCS interval  $\Delta t$ , during which  $v$  decreases, resulting in a finite deceleration  $a$ . To reduce this deceleration, which serves as a key metric directly related to dynamic instability, we propose a Compliant Spiral Torsional Suspension (C-STs) attached between the motor and the wheel's rotational axis as shown in Fig. 1(b).

Fig. 1(c) illustrates the operating principle of the proposed C-STs. The C-STs is wound by the relative angular displacement  $\Delta\theta = \theta_M - \theta_W$  between the motor and wheel angles,  $\theta_M$  and  $\theta_W$ , and stores or releases elastic energy in the torsional direction. The expected role of the C-STs can be summarized in four stages. First, when the wheel is initially stationary, the motor winds the C-STs and stores energy in the spring. As the spring generates a forward-driving torque  $\tau_s$ , the wheel begins to rotate once the supplied torque becomes large enough to overcome the gravitational potential

barrier (Initial charge). Second, after the wheel enters the CCS, it rolls under the spring torque while maintaining a roughly sustained level of stored spring energy. Third, when the wheel enters the DCS and undergoes contact transition, the C-STs provides torsional compliance between the motor and wheel, allowing a rapid release of spring energy to the wheel. This causes an instantaneous increase in the wheel angular velocity  $\omega_w$ , which raises the minimum post-transition velocity and thereby reduces  $\Delta v$ . Lastly, the same compliance extends the DCS interval  $\Delta t$ . As a result, through reduced  $\Delta v$  and increased  $\Delta t$ , the proposed C-STs can reduce the corresponding deceleration  $a$  and improve dynamic stability during stair climbing.

To realize the intended functions described above, we designed the structure such that the C-STs, placed between the motor and wheel axes, operates in a manner like a serial elastic actuator. To evaluate its performance, two test platforms were fabricated: a basic configuration where the CSTW is rigidly connected to the motor without C-STs, and a C-STs configuration where the C-STs is installed between the motor and the wheel. Experiments were conducted using a 6kg test robot on a three-step staircase with a tread length of 300mm and a riser height of 160mm.

Four scenarios were considered: S1 without a C-STs, and S2, S3, and S4 with low, medium, and high torsional stiffness, respectively. The experiments were performed under three motor angular velocity conditions ( $\omega_M = 3.2, 8.5, 13$  rad/s) and three torsional stiffness conditions ( $k_t = 0.206, 0.547, 0.909$  N·m/rad). For each scenario, the climbing test was repeated three times at each angular velocity condition, resulting in a total of 36 experiments.

Through the experiments, two types of performance metrics were evaluated. First, the primary metric for quantifying dynamic stability was defined as the DCS deceleration  $a_i$ , which is governed by  $\Delta t_i$  and  $\Delta v_i$ ; a smaller  $a_i$  indicates more stable behavior. In addition, overall climbing performance was assessed using two supplementary metrics. The first is the mean velocity  $\bar{v}$ , defined as the average value of  $v$  during stair climbing, where a higher value indicates faster climbing. The second is the standard deviation of velocity,  $s$ , where a lower value indicates that the velocity remains more closely distributed around  $\bar{v}$ , reflecting more uniform climbing performance.

Regarding the DCS deceleration results,  $a_i$  showed a noticeable reduction at medium and high speeds in the mid- and high-k C-STs cases, compared with the basic scenario without the C-STs. In particular, the mid-k, high-speed scenario achieved the largest reduction, reaching 23.7%. In contrast, the small-k C-STs did not show a meaningful reduction even under same speed conditions. More critically, under the low-speed condition, all C-STs cases exhibited substantially larger deceleration than the basic one, with increases ranging from 30% to 37%.

Under the medium- and high-speed conditions, the lack of improvement in the small-k case can be explained by the

combined behavior of  $\Delta t_i$  and  $\Delta v_i$ . Although  $\Delta t_i$  became longer than in the basic case, the spring could not provide sufficient torque to the wheel during contact transition, and thus the velocity gap was not effectively reduced. Without instantaneous increase in  $\omega_w$ , a longer transition may be accompanied by a larger velocity drop, offsetting the increase in  $\Delta t_i$  and resulting in a larger  $a_i$ .

The poor performance of all C-STs cases at low speed is attributed to early unwinding before the DCS. Because the spring, wound during the preceding CCS, gradually releases energy while overcoming gravitational potential energy, a longer CCS at the low speed leaves in sufficient stored energy for rapid release at contact transition. As a result, the spring cannot provide the desired support at the onset of the DCS, leading to degraded dynamic stability.

Finally, regarding the overall climbing performance metrics, all C-STs cases produced higher  $\bar{v}$  than the basic case under the high-speed condition, with the high-k case achieving the largest increase of 11.7%. In contrast, a reduction in  $s$  was observed only in the high-speed, high-k scenario, where it decreased by 17.5% relative to the basic case. This suggests that the high-speed, high-k condition yields both a higher average climbing speed and a more consistent velocity profile.

In conclusion, the proposed C-STs improved stability only within a limited range of angular velocity and stiffness conditions. This indicates that its effectiveness is governed by a complex interaction among dynamic factors, including the mass-stiffness ratio, angular velocity, and the precise timing of energy release. Accordingly, future work should establish a hybrid dynamic model that accurately captures the CSTW-C-STs system and identifies the conditions under which the C-STs can operate most effectively. Beyond this specific platform in our research, the present findings suggest that passive torsional compliance may offer a useful solution for other wheel mechanisms subject to similar instability.

**Keyword** – Mobile robot, Curved-spoke tri-wheel, Stair obstacle, compliant mechanism, Dynamic stability

## REFERENCES

- [1] Jeong S, Kim Y, "Experimental Investigation of a Passive Compliant Torsional Suspension for Curved-Spoke Wheel Stair Climbing", *Applied Sciences*, 2025, 15(11):5985, doi: 10.3390/app15115985.
- [2] Y. Kim, J. Kim, H. S. Kim and T. Seo, "Curved-Spoke Tri-Wheel Mechanism for Fast Stair-Climbing," in *IEEE Access*, vol. 7, pp. 173766-173773, 2019, doi: 10.1109/ACCESS.2019.2956163.
- [3] Václav Kryš, Zdenko Bobovský, Tomáš Kot, Jiří Marek, "Synthesis of action variable for motor controllers of a mobile system with special wheels for movement on stairs", *Perspectives in Science*, Volume 7, 2016, Pages 329-332, ISSN 2213-0209, doi: 10.1016/j.pisc.2015.11.050.
- [4] Sharda Prasad Agrawal, Haresh Dagale, Nirmal Mohan, and L. Umanand, "IONS: A Quadruped Robot for Multi-terrain Applications," *International Journal of Materials, Mechanics and Manufacturing* vol. 4, no. 1, pp. 84-88, 2016.