Development of a Linear Actuator-Based Transformable Wheel-Based Bipedal Robot for Enhanced Mobility in Nuclear Facilities

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1. Introduction

In the event of an accident within nuclear facilities requiring emergency intervention in hazardous areas, the deployment of robotic platforms is essential to ensure worker safety and perform continuous environmental monitoring [1, 4]. As radiation environments severely limit the permissible operational time for teleoperation by human workers, dispatched robots must be capable of maneuvering swiftly and reliably. Furthermore, the internal environment of a nuclear facility is highly unstructured. Internal stairs and structural obstacles in these target facilities typically feature a maximum step height of 15 cm. Consequently, the robotic platform must be mechanically capable of overcoming this 15 cm vertical obstacle to ensure seamless, enhanced mobility across restricted areas [1].

Initially, a four-wheeled quadruped robot was conceptually designed to provide maximum static stability during such complex step-climbing tasks. However, the inherently wide footprint and extended lateral stance of the quadruped structure proved structurally unsuitable for the highly constrained corridors, typically measuring 90 cm in width, commonly found in nuclear plants, which are often congested with piping and valves. To resolve this critical spatial limitation without compromising the robot's payload capacity, the design strategy strategically transitioned to a transformable wheel-based bipedal robot (WBR) [3]. This modified WBR configuration reduces the overall width to 57 cm, maximizing maneuverability in confined spaces while safely satisfying the step-climbing requirements.

Therefore, this study presents a systematic hardware developmental progression aimed at enhanced mobility. First, the required actuator specifications are extracted using the initial quadruped kinematic model. Second, a highly efficient custom linear actuator is developed based on the derived data. Third, the hardware is reconfigured into a compact WBR that meets strict spatial constraints and maintains operational stability through an innovative transforming mechanism. Finally, the platform's specifications are verified against the stringent requirements of nuclear facilities.

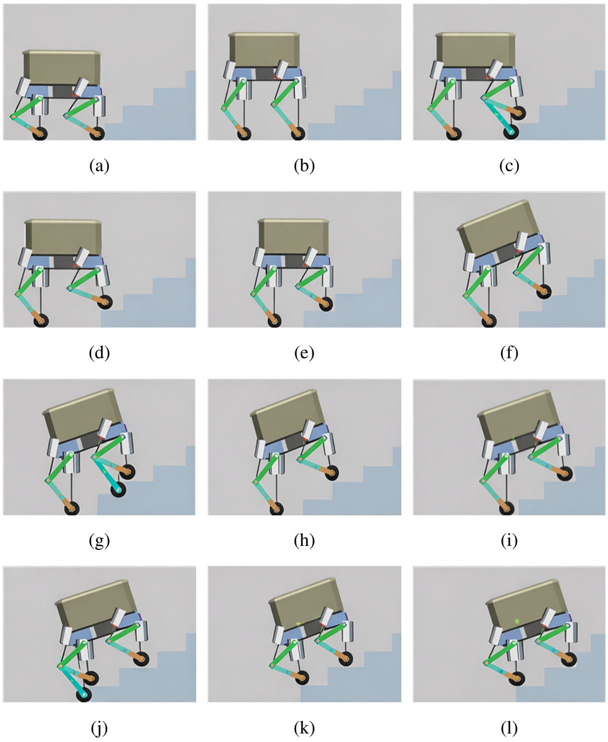

Fig. 1. Step-climbing sequence (phases 0 to 11) based on the initial quadruped kinematic model: (a)–(l) represent the sequential motion of the robot overcoming a 15 cm obstacle.

2. Methods and Results

2.1 Initial concept and static analysis

To theoretically deduce the maximum load applied to the robot's leg joints during a 15 cm vertical displacement, an 11-stage step-climbing scenario was systematically constructed based on the initial 4-legged kinematic model, as illustrated in Fig. 1.

The scenario details the precise combination of leg joint articulation and wheel driving required to safely overcome obstacles without losing balance. On flat terrain (Phase 0, Fig. 1(a)), the robot utilizes only the in-wheel motors to maximize energy efficiency. When approaching stairs, the front leg joints actuate to lift and place the front wheels onto the elevated step (Phases 1-2, Fig. 1(b)-(c)). Once secured, the wheels drive the robot forward (Phases 3-4, Fig. 1(d)-(e)), effectively shifting the center of gravity over the new pivot point.

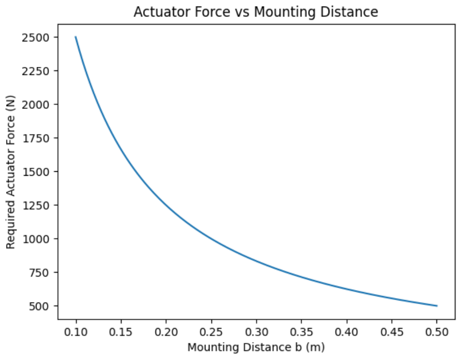

Fig. 2. Required actuator force vs. mounting distance (b).

Subsequently, the rear legs actuate to lift the rear wheels onto the elevated terrain (Phases 5-8, Fig. 1(f)-(i)). Finally, the robot adjusts its posture to fully stabilize the body (Phases 9-11, Fig. 1(j)-(l)). Assuming a maximum platform mass that includes heavy inspection payloads, this sequential analysis guarantees that the absolute maximum load conditions (worst-case scenario) for the actuators are accurately calculated.

To enhance space and energy efficiency within the hardware structure, a recti-linear driving mechanism was adopted over conventional rotary joints [2]. Linear actuators inherently provide a higher payload-to-weight ratio, which is advantageous for legged locomotion. Static analysis based on the step-climbing scenario was performed to determine the optimal installation position of the linear actuator.

As shown in Fig. 2, the required joint force decreases significantly as the mounting distance b increases. However, overly extended mounting distances cause structural interference during walking and limit the range of motion. To prevent kinematic interference while minimizing the required force, the optimal installation position was determined to be $b = 0.1$ m. Based on this baseline, the required stroke distances for the upper and lower linear actuators were calculated as 66 mm and 160 mm, respectively.

2.2 Development of linear actuator

To meet the required driving torques of 0.19 Nm and 0.44 Nm for the upper and lower joints, respectively, custom linear driving units were designed based on the quadruped model. By integrating spur gears with reduction ratios of 2:5 and 5:11, the actuators successfully secure a target linear speed of 0.2 m/s utilizing compact 50W and 100W-class motors.

Comprehensive performance evaluations were conducted on a custom dynamometer testbed to verify load-carrying capacity and reliability under continuous operation. The experimental results demonstrated that the 60W-class linear actuator achieved a maximum force of approximately 310 N and a speed of 0.19 m/s. The 100W-class actuator produced a maximum of 480 N of

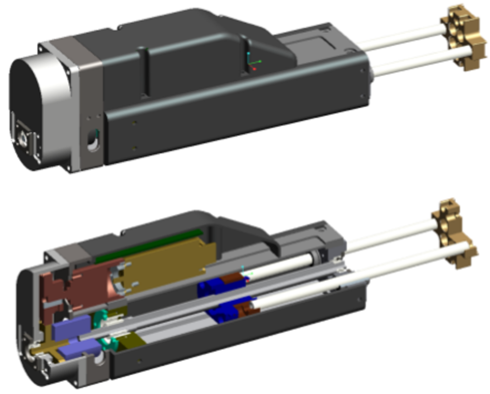

Fig. 3. 3D CAD design of the custom-developed linear actuator.

force and 0.16 m/s of speed, effectively satisfying the heavy-duty requirements for lifting the robot's payload during step-climbing operations without thermal degradation.

2.3 Design modification: Transformable WBR

While the initial quadruped design theoretically ensured stable step-climbing, its physical width exceeded the spatial limits of typical nuclear corridors. To address this issue, the hardware design was modified into a transformable WBR, retaining the proven leg mechanisms and the newly developed linear actuators. The final hardware module was strictly constrained to maintain an overall width of 57 cm, as shown in Fig. 4.

On flat terrain, the robot maneuvers at high speeds using MDH180 in-wheel motors equipped at the base of the legs, achieving a linear speed of 1.4 m/s. This wheeled locomotion is substantially more energy-efficient than traditional walking.

To overcome the inherent lack of static stability associated with bipedal forms during stationary or precise manipulation tasks, an innovative transforming structure was adopted [5]. As illustrated in Fig. 4, caster wheels are mounted on the robot's knees. By deploying these knee-mounted caster wheels, the robot lowers its center of gravity and significantly expands its support polygon. Supported by a total of four wheels (two in-wheel motors and two caster wheels), this transforming mechanism ensures that the zero moment point remains strictly within the stable region during delicate tasks. This functionally mimics the high stability of a quadruped while maintaining the slim profile of a biped.

2.4 Performance Evaluation for Nuclear Environments

To validate the practical applicability of the developed robotic platform, its final hardware specifications and performance metrics were comprehensively compared against the environmental requirements of nuclear facilities.

As detailed in Table 1, the developed WBR success-

Table 1. Comparison of Target Requirements and Achieved Performance

Category	Target Requirement	Achieved Performance
Maximum step height	15 cm vertical displacement	Mechanically designed to safely clear 15 cm
Overall width	Maximum 90 cm	Designed with a strict width of 57 cm
Flat terrain speed	Minimum 10 cm/s	In-wheel motor achieves 1.4 m/s
Terrain adaptability	Overcoming stairs and uneven terrain	Adopted transformable WBR structure
Actuator force	Capable of worst-case climbing scenario	Secured maximum 310 N and 480 N

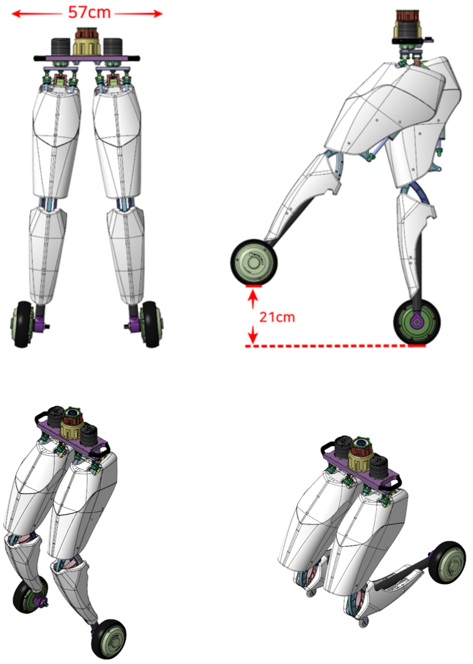

Fig. 4. Overall dimensions (top) and transforming mechanism utilizing caster wheels (bottom) of the modified WBR.

fully fulfills all necessary criteria. The overall width of 57 cm allows for safe passage through the narrowest 90 cm corridors, while the developed linear actuators generate sufficient force to conquer 15 cm step heights. Furthermore, the 1.4 m/s in-wheel driving speed exceeds the minimum requirement, enabling rapid responses to emergency scenarios. The transforming mechanism effectively resolves the operational challenges between narrow spatial passage and stability on uneven terrain.

3. Conclusion

This study demonstrated a systematic hardware development process tailored for a nuclear facility mobility platform. By utilizing an initial quadruped kinematic model, the maximum step-climbing loads were precisely derived, leading to the development and experimental validation of high-efficiency custom linear actuators.

Ultimately, the robotic platform was systematically reconfigured into a transformable WBR. As verified through the performance evaluation, this platform overcomes the strict spatial constraints of nuclear corridors by maintaining a compact width of 57 cm, while maintaining the vital ability to climb 15 cm steps. The proposed transforming design effectively resolves the trade-off between spatial adaptability and structural stability. This hardware provides a highly viable and reliable foundation for enhanced mobility, autonomous inspection, and manipulation missions in extreme environments.

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