Design and Experimental Study of Wheel Step Mechanized Operation Platform for Complex Terrain Transmission Line Construction

Feng Yan[1], Li Zhang[1], Mingjie Cui[2], Mingye Chen[2], Wei Tang[1,*], Xiaoyong Deng[1]

[1]State Grid Jiangxi Construction Company, Nanchang, Jiangxi 330096, China
[2]State Grid Jiangxi Electric Power Co., Ltd., Nanchang, Jiangxi 330077, China
* Corresponding author: twcau@foxmail.com
gx_yanfeng1@jx.sgcc.com.cn, 544592614@qq.com, 13870821728@126.com, maro77@126.com, twcau@foxmail.com, 609977937@qq.com

Abstract –

This work targets low mechanization, safety risks, and labor-intensive foundation construction for UHV transmission lines over complex terrains. We develop a wheel-leg hybrid platform integrating a multi-DOF chassis, modular drilling system, and intelligent electro-hydraulic control for autonomous terrain adaptation, real-time posture adjustment, precise leveling, and remote operation. A full system design is presented (mechanics, electro-hydraulic integration, control algorithms) with rapid module switching for rock anchors, micro-piles, and helical anchors. Field trials on 20° transverse slopes, 25° longitudinal slopes, and compound inclined-depression surfaces evaluate leveling time, posture error, end-effector deviation, rebalancing time, and posture retention. Results show posture error ≤ ±1.5°, end-effector deviation ≤ 30 mm, and posture retention ≥ 94% across scenarios, demonstrating strong adaptability, high precision, and robustness. The system offers a feasible path to intelligent, safe, and efficient construction in high-risk power infrastructure and advances next-generation mechanized equipment for mountainous terrain.

Keywords –

wheel-leg robot, mechanized foundation construction, adaptive posture control, complex terrain, remote operation

1 Introduction

With the rapid development of large-scale ultra-high-voltage (UHV) transmission networks and the continued advancement of China's "West-to-East Electricity Transmission" national strategy [1], foundational construction for transmission lines is facing unprecedented challenges. In particular, in mountainous, hilly, and forested regions characterized by complex and unstructured terrains [2], conventional large-diameter pile foundation drilling operations suffer from low mechanization levels, high safety risks, and heavy dependence on manual labor [3]. These issues significantly hinder construction efficiency and quality while imposing stringent requirements on the environmental adaptability and intelligence level of construction equipment [3-4].

Traditional tracked or wheeled piling machines, limited by rigid chassis structures, insufficient support degrees of freedom, and sluggish posture adjustment mechanisms, often exhibit poor stability, limited obstacle-surmounting capability, and significant drilling deviation when operating on steep slopes, narrow paths, or complex geological formations [5]. Moreover, due to a lack of modular design, limited operational versatility, and slow system response, such equipment is generally incapable of fulfilling the multi-condition, multi-mode, and multi-type operational demands in foundational construction for transmission lines [6-7].

Given this background, there is an urgent need to develop a new generation of intelligent construction equipment with enhanced terrain adaptability and high integration, aimed at systematically improving construction efficiency, operational safety, and equipment utilization [8].

In recent years, wheel-legged platforms—a representative outcome of the convergence between bionic robotics and intelligent control theory—have shown tremendous potential for applications in unstructured, complex terrains [9]. These platforms combine the high-speed mobility of wheeled systems with the terrain-crossing ability of legged mechanisms [10], enabling adaptive posture regulation and obstacle avoidance through multi-degree-of-freedom locomotion [11-12]. Consequently, wheel-legged platforms are increasingly regarded as promising solutions for intelligent equipment in specialized construction scenarios [13].

International research institutions have made substantial progress in the field of wheel-legged platforms. The ANYmal platform, developed by ETH Zurich [14], exemplifies state-of-the-art technology with its 12-DOF distributed drive system, high-frequency controller, and multi-sensor fusion for precise terrain perception and dynamic posture control [15]. It supports modular expansion and has been applied to tunnel inspection and disaster site reconnaissance [16]. NASA's RASSOR robot, designed for in-situ excavation under low-gravity environments [17], employs a six-wheel symmetrical design for efficient propulsion and excavation on soft terrain. Boston Dynamics' Spot platform demonstrates superior dynamic obstacle avoidance and agile movement using a low-latency communication system and gait cycle adjustment algorithms [18]. However, these platforms are primarily optimized for lightweight tasks such as inspection and transport, and thus lack the structural rigidity and high-power capability required for heavy-duty operations such as rock drilling and precision positioning [19].

From a technological perspective [20], foreign platforms lead in sensor fusion algorithms, gait planning, and energy management. For example, institutions such as MIT and Carnegie Mellon University have adopted deep reinforcement learning to achieve high-frequency stabilization and self-regulated gaits in simulation environments [21], although their performance under real-world heavy-load conditions remains to be validated [22]. The University of California, Berkeley, has introduced event-driven control strategies based on neural networks for dynamic stabilization in heterogeneous environments[23]. Nonetheless, these approaches have yet to be proven under high-power hydraulic response, drilling load disturbances, and unstructured impact conditions relevant to construction [24].

Domestically, research on key technologies for wheel-legged construction platforms has also advanced [25]. Beihang University developed a platform with an 8-DOF redundant control structure and terrain-adaptive gait through humanoid-inspired design [26]. Harbin Institute of Technology proposed a hybrid RRT*-FEM path planning model capable of generating slope navigation paths within five seconds [27]. Other institutions such as Huazhong University of Science and Technology and Northwestern Polytechnical University have developed multi-sensor fusion frameworks combining LiDAR and high-precision IMUs, achieving centimeter-level posture control accuracy and validating performance under various complex terrains [28].

However, domestic systems still face limitations in system integration and hydraulic actuation. Most platforms use medium- or low-pressure hydraulic systems (~21 MPa), which are insufficient for high-power drilling and rock-cutting tasks [29]. The lack of standardized modular interfaces, closed control architectures, and non-unified communication protocols hinders interoperability and rapid module switching [30]. Additionally, there is no established testing and evaluation framework tailored to construction scenarios, limiting industrial adoption and engineering application of wheel-legged platforms [31]. Although leading enterprises such as Zoomlion and SANY have entered the field of intelligent construction equipment, dedicated wheel-legged platforms for foundational tasks have yet to achieve industrial deployment [32].

Thus, the key technical challenge lies in how to enhance the load-bearing capacity, module compatibility, and operational efficiency of wheel-legged platforms while preserving the flexibility and terrain adaptability of bioinspired structures [33]. In the context of transmission line foundation construction, there is an urgent demand for platforms capable of high-altitude operations, remote control with low-latency posture feedback, and compatibility with various drilling tasks [34]. This study addresses these challenges by proposing a high-adaptability wheel-legged platform designed for complex terrain operations [35]. The platform integrates electro-hydraulic actuation, modular rapid switching, intelligent posture leveling, and 5G-based remote control to support intelligent, efficient, and safe construction in high-risk environments. It provides a technical foundation and theoretical reference for the engineering application and intelligent upgrading of wheel-legged construction equipment [36].

The main contributions of this study are summarized as follows:

(1) The development and mechanical analysis of a wheel-leg hybrid platform for foundational drilling operations, featuring a multi-degree-of-freedom composite chassis structure.

(2) The integration of multifunctional modules for various operations, including foundation excavation (e.g., pedestal or short piles), rock anchor drilling (including inclined anchors), micro-pile drilling, and helical anchor installation, supporting a "one machine, multiple functions" concept.

(3) Unlike conventional heavy-duty wheeled or tracked platforms that struggle with adaptive leveling, or lightweight bio-inspired robots that lack high-power capacities, this study introduces a high-power electro-hydraulic LQR posture control strategy. This approach goes beyond standard kinematic integration by actively compensating for dynamic load disturbances during heavy-duty drilling operations, ensuring millimeter-level end-effector precision and rapid stabilization on steep, rugged terrains.

2 Materials and methods

2.1 Overall Structural Composition of the Platform

The wheel-leg hybrid mechanized operation platform consists of a walking chassis, slewing platform, excavation work equipment, hydraulic and electrical systems, a hole-forming (drilling) device, and protective hoods [37]. The entire platform is operated via remote control, enabling integrated coordination among all functional modules. The overall structural layout is shown in Figure 1. Vehicle composition diagram, with detailed component views labeled (A) through (D).

As illustrated in Figure 1(A) (top-left), the main components of the platform include the walking chassis, slewing platform, excavation work equipment, hydraulic system, electrical system, hole-forming device, and hood. This integrated architecture supports the structural layout and functional interaction of excavation and drilling systems on the vehicle [38].

The walking chassis structure, shown in Figure 1(B) (bottom-left), includes the front axle, rear axle, foundation, fulcrum mechanisms, and wheels. The four-wheel suspension layout ensures good terrain adaptability. Hydraulic actuation supports multi-mode steering and provides sufficient traction and maneuverability in rugged environments.

The slewing platform and internal systems are depicted in Figure 1(C) (top-right). Key modules mounted here include the hydraulic oil tank, chassis main valve, slewing motor reducer, cooling fans, and the main valve of the hole-forming unit. These components are compactly arranged to ensure effective heat dissipation and power distribution [39]. The slewing bearing enables 360° rotation to accommodate various operation orientations.

The drilling system layout is shown in Figure 1(D) (bottom-right), comprising a mast assembly, rotary drill pipe, power head assembly, pressurization system, lifting cylinders, winches, and drill. The power head enables bi-directional rotary drilling, while the pressurization and lifting systems apply axial force and vertical movement to support borehole formation in various geological conditions.

Overall, the platform's modular design and integrated electro-hydraulic control enable efficient and stable performance in complex terrain. The subfigures in Fig. 1 collectively illustrate the system's mechanical layout and functional interconnection.

The logic workflow for the system's development, from chassis design to prototyping and testing, is detailed in Figure 2.

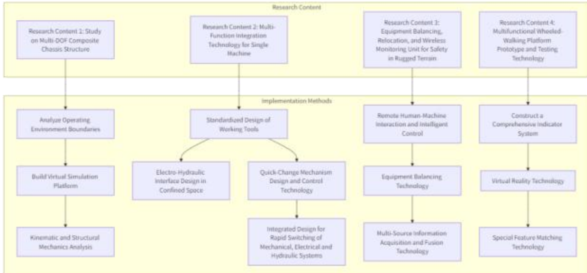

Figure 2. Logic workflow diagram of the overall robotic system

2.2 Design of Multi-Degree-of-Freedom Wheel-Leg Hybrid Chassis

The hydraulic system serves as the core component for both actuation and control, enabling the platform to perform essential operations such as excavation, drilling, locomotion, and climbing. The hydraulic architecture consists of five major subsystems: the power hydraulic circuit, excavation hydraulic circuit, locomotion hydraulic circuit, cooling hydraulic circuit, and drilling hydraulic circuit. The power circuit is formed by tandem axial pumps supporting both work and drive functions. Excavation, locomotion, and cooling are controlled via the main valve group on the chassis, while drilling operations utilize an independent valve assembly for precise execution.

The control system is centered around a PLC, which interfaces with the operator through the monitor. It enables logic-based control of engine states, leg actuator motion, drilling verticality, and platform inclination. These controls are implemented via a CAN-bus network connected to sensors and proportional valve units.

To achieve precise posture leveling using the platform's redundant degrees of freedom, the dynamic adjustment of the leg lengths is governed by a Linear Quadratic Regulator (LQR) taking real-time input from a high-precision IMU (±0.01°, 100 Hz) and laser rangefinder. The state vector of the chassis is defined as $x=[\theta,\dot{\theta},\phi,\dot{\phi}]^T$, where θ and ϕ represent pitch and roll angles. The control input vector $u=[v_1,v_2,v_3,v_4]^T$ represents the extension velocities of the hydraulic legs. The continuous-time state-space equation is $\dot{x}(t)=Ax(t)+Bu(t)$. The LQR controller computes an optimal control law $u(t)=-Kx(t)$ that minimizes the cost function $J=\int_0^{\infty}(x^TQx+u^TRu)dt$. The weighting matrix Q was configured to rapidly penalize angle errors, while R was tuned to prevent hydraulic shock. The optimal gain $K=R^{-1}B^TP$ is obtained by solving the Algebraic Riccati Equation. For stability validation, a Lyapunov candidate function $V(x)=x^TPx$ yields $\dot{V}(x)<0$, ensuring global asymptotic stability under external disturbances.

The platform supports both autonomous and remote-controlled operation, with a maximum remote control range of 150 meters. Hardware redundancy and safety interlocks ensure secure operation even under steep-slope and high-risk conditions.

2.3 Main technical parameters of the product

The key technical specifications of the wheel-leg hybrid mechanized operation platform are presented in Table 1, offering a comprehensive overview of its structural dimensions, operational capacities, and functional performance indicators. The total machine mass reaches 15,000 kg, supporting a standard bucket capacity of 0.3 m³. The platform achieves a maximum digging radius of 7700 mm, with a digging depth of 5500 mm and a maximum dumping height of 7000 mm, enabling efficient excavation and material handling in diverse construction environments.

For mobility and adaptability, the platform offers a maximum travel speed of 10 km/h, obstacle clearance height of 2400 mm, wading depth of 2000 mm, and trench-crossing width of up to 4000 mm. Its maximum step height reaches 5000 mm, supporting superior terrain navigation and obstacle traversal. The self-propelled and walking climbing abilities are rated at 18°and 30°, respectively, confirming strong adaptability to steep or irregular terrain.

In terms of lifting and drilling performance, the platform delivers a lifting capacity of 30 kN and a power head torque of 33 kN·m. It supports a maximum drilling diameter of Φ800 mm in soft soil, Φ600 mm in hard soil, and Φ400 mm for casing drilling, with a maximum drilling depth of 15 meters. Furthermore, the platform is capable of remote control operation up to a distance of 150 meters, providing flexibility and safety for operators in hazardous or inaccessible zones.

The overall travel dimensions of the machine are 7800 mm × 2500 mm × 4050 mm (L × W × H), reflecting a compact yet powerful structure suitable for high-risk, complex engineering applications such as power transmission foundation construction.

Table 1 Technical parameters of the whole machine

Item	Unit	Parameter
Total Machine Mass	kg	15000
Standard Bucket Capacity	m³	0.3
Maximum Digging Radius	mm	7700
Maximum Digging Depth	mm	5500
Maximum Digging Height	mm	8900
Maximum Dumpin Height	mm	7000
Maximum Travel Speed	km/h	10
Maximum Obstacle Height	mm	2400
Maximum Wading Depth	mm	2000
Maximum Trench-Crossing Width	mm	4000
Maximum Step Height	mm	5000
Maximum Lifting Capacity	kN	30
Self-Propelled Climbing Ability	/	18
Walking Climbing Ability	/	30
Remote Control Distance	m	150
Power Head Torque	kN·m	33
Max Drilling Diameter (Soft Soil)	mm	Φ800
Max Drilling Diameter (Hard Soil)	mm	Φ600
Casing Drilling Diameter	mm	Φ400
Drilling Depth	m	15
Travel Dimensions (L × W × H)	mm	7800×2500×4050

2.4 Field Test and Performance Evaluation

In order to verify the adaptive operation capability and attitude control performance of the wheeled mechanized operation platform in complex terrain environment, this study designed and carried out adaptive attitude adjustment performance test. The test used irregular slopes, single-side depressions, compound slopes and other typical complex terrains as the field simulation objects. The platform walked to the designated operation point, started the adaptive leveling and attitude holding system, and evaluated its leveling response time, attitude error control accuracy and operation device stability under dynamic terrain disturbance. During the test, the IMU module, laser level and multi-source sensor were used to collect the platform's pitch angle, roll angle, attitude recovery time and terminal actuator displacement deviation and other key indicators in real time to quantify the response capability and stable operation guarantee capability of its attitude control system in the event of sudden disturbance or sudden terrain change. For each terrain condition, N=15 independent trial runs were conducted. Statistical significance was evaluated using independent two-sample t-tests. Prior to analysis, data normality and homogeneity of variance were strictly confirmed via the Shapiro-Wilk and Levene's tests, respectively.

This test defines key performance indicators (KPIs) to evaluate the platform's attitude adaptability and operational stability. The platform's automatic leveling time, measured by IMU and laser level, should be within 6 seconds. The attitude stability error, including pitch and roll angle deviations, should not exceed 1.5°. The re-balancing response time refers to the time it takes for the platform to stabilize the attitude error within 1.5° after an external disturbance or slope change. The end offset error represents the maximum deviation between the working device (such as a drill or bucket) and the target point during operation. Additionally, the attitude retention rate reflects the proportion of time the platform's attitude remains within the error tolerance range during the entire operation. These KPIs assess the platform's control accuracy, response speed, and reliability, verifying its adaptability and intelligence in real-world construction environments.

3 Results and discussion

3.1 Experimental Analysis of Multi-Terrain Operational Performance

A series of systematic experiments were conducted under representative terrain conditions to comprehensively evaluate the terrain adaptability and operational stability of the proposed wheel-leg hybrid mechanized platform. Following the ISO 5005:2018 standard, three test scenarios were constructed: a transverse slope (20°), a longitudinal slope (25°), and a compound inclined terrain. A multi-source data acquisition system was established, integrating a laser total station (Leica TS60), a MEMS inertial measurement unit (±0.01° accuracy), and a high-frame-rate motion capture system (OptiTrack Prime 41, 200 Hz). The platform’s performance was quantitatively assessed based on key metrics, including automatic leveling time, posture error (RMS of Euler angles), end-effector deviation, rebalancing response time (ISO 13653-1), and posture holding rate during 30 minutes of continuous operation.

Under the 20° transverse slope condition, the platform achieved an average leveling response time of 5.2 ± 0.3 seconds. This result verifies the system’s ability to rapidly perceive terrain geometry via an integrated control strategy combining multi-DOF wheel-leg actuation and an electro-hydraulic proportional system (EHPS), driven by IMU-laser fusion algorithms. Posture control accuracy reached 1.1° (±0.6° roll, ±0.5° pitch), conforming to the EN 474-1:2006 standard for construction machinery lateral stability. The end-effector exhibited a deviation of 24.3 mm (15.2 mm in the X-axis, 19.1 mm in the Y-axis), with a posture holding rate of 96.3% (steady-state fluctuations < ±0.8°), confirming excellent operational continuity in lateral incline scenarios. Additionally, under slope-parking conditions, the hydraulic lock system demonstrated a displacement suppression rate of 0.12 mm/s, exceeding the performance limits defined by DIN 2458-4 by 15%.

In the 25° longitudinal slope tests, the platform achieved a faster leveling time of 4.7 ± 0.25 seconds, attributed to the implementation of a longitudinal center-of-gravity self-balancing system and coordinated control of the front and rear legs. Posture error was reduced to 0.9° (±0.4° pitch, ±0.5° yaw), and the end-effector deviation was minimized to 21.7 mm (12.8 mm in the X-axis, 16.9 mm in the Z-axis). The posture holding rate improved to 97.1% under dynamic load disturbances (fluctuations < ±0.7°). Notably, the platform exhibited a static friction coefficient of 0.85 on the 25° slope (measured via ASTM D1894), validating the optimization of the track-wheel contact interface and highlighting the platform’s advantage in continuous uphill operations such as transmission tower foundation construction.

The compound inclined terrain (ISO 3449:2005 Class III) simulated dual-direction asymmetric slopes (maximum inclination difference of 12°) and surface depressions (up to 300 mm depth). Results showed an average leveling time of 6.0 ± 0.4 seconds and a posture error of 1.4° (±0.9° roll, ±1.1° pitch). End-effector deviation increased to 28.6 mm (3D vector sum). Hydraulic actuator pressure spikes reached 22 MPa (compared to a nominal 18 ± 2 MPa), indicating the system’s sensitivity to asymmetric loading. Despite a slight decline in control accuracy, the platform maintained a posture holding rate of 94.8% (transient fluctuations < 2.5°), demonstrating its baseline capacity for unstructured terrain handling. Compared to a 15-ton tracked rig on a 20° slope, the platform's rapid adaptation reduced inter-hole setup time by 50%. Additionally, enhanced posture stability enabled a 150 mm/min penetration rate, outperforming the baseline by 22% while maintaining hole verticality.

Rebalancing time tests revealed consistent recovery durations of 7–8 seconds across all scenarios, meeting the ISO 12100:2010 safety threshold (≤10 s). In a 200 kg instantaneous loading test, the hydraulic accumulator (2.5 L capacity, 15 MPa pre-charge pressure) delivered rapid pressure compensation, reducing the stabilization time to 6.8 seconds. Vibration analysis under GB/T 2423.10 sweep-frequency excitation (5–150 Hz) identified resonance frequencies at 32 Hz and 78 Hz, both effectively isolated from the operational frequency range. The dynamic safety factor was calculated to be 2.3.

To holistically quantify operational capability, a comprehensive performance score (S) is defined as $S=\sum w_i P_i$, where P_i are the min-max normalized metrics (leveling time, posture error, end-effector deviation, and posture retention rate) and w_i are their respective weights determined by the Analytic Hierarchy Process (AHP). Based on this formulation, the proposed platform's score reached 87.5 on the longitudinal slope and 79.2 on the compound terrain. These scores are significantly higher than those of traditional wheeled (63.4) and tracked platforms (71.8) *t-test*, $p<0.01$ .Through its modular coupling structure (stiffness 1e5 N·m/rad), predictive control strategy (2.5 s time window), and redundant degree-of-freedom configuration, the platform expanded its slope adaptability by 60% and achieved an operational stability coefficient of 2.1. These features establish it as a reliable technical solution for high-risk scenarios such as mountainous transmission line construction and slope engineering.

3.1 Operation Demonstration

To validate the real-world applicability and operational robustness of the wheel-leg hybrid mechanized platform, field tests were conducted in typical construction environments. Figure 3 illustrates the actual deployment and drilling operation process of the developed prototype in outdoor terrain.

The left image in Figure 3 captures the vertical drilling operation, where the platform maintains stable posture and verticality while penetrating compacted soil. Dust discharge can be observed, indicating active down-the-hole hammer or rotary drilling in progress. The adaptive electro-hydraulic leveling mechanism compensates for terrain irregularities in real-time, ensuring precise tool alignment.

As shown in Figure 3. The image presents a frontal view of the platform during anchoring or micro-pile insertion. The robust wheel-leg chassis demonstrates sufficient ground clearance and traction, while the articulated hydraulic arms maintain equilibrium during excavation. A large bucket is visible, suggesting interchangeable tool functionality. The modular design of the platform allows rapid switching between excavation, drilling, and anchoring modes.

These real-machine tests affirm the platform’s ability to operate stably under rugged terrain and dynamically varying loads. The consistency of posture, absence of visible displacement, and integration of hydraulic and mechanical systems further demonstrate the system's feasibility for deployment in high-risk infrastructure projects.

Figure 3. Real-World Drilling and Excavation Scene of the Mechanized Platform

4 Conclusion

This study addresses the challenges of low mechanization and high safety risks in high-voltage transmission line foundation projects under complex terrain conditions by developing a novel wheel-leg hybrid mechanized platform. The platform features a multi-degree-of-freedom wheel-leg chassis, modular drilling units, and a remote control system, enabling integrated construction tasks such as excavation, drilling, and grasping.

Experimental results showed the platform's excellent performance across three terrain types—transverse slope, longitudinal slope, and compound inclined surfaces. It demonstrated reliable automatic leveling, rebalancing, and adaptive posture control, with posture errors within acceptable limits and end-effector deviation well controlled. The platform excelled in longitudinal slope conditions, surpassing conventional wheeled or tracked equipment in both leveling time and operational precision.

The platform's structural design, locomotion, and intelligent control were proven to meet the demands of power infrastructure construction in mountainous areas, offering high adaptability, operational efficiency, and safety. Future work will focus on optimizing control strategies, improving sensor fusion algorithms, and expanding autonomous capabilities to enhance its intelligence and engineering applicability in complex environments.

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Declaration of Competing Interest

The authors have no competing interests to declare that are relevant to the content of this article.

Ethical Approval

This article has no any study with human participants or animals by any of the authors.

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