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A review of research on hybrid unmanned vehicles in complex forest and grassland terrains

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Abstract: The sustainable management of European forest ecosystems necessitates innovative mechanisation solutions to address operational challenges in hilly, mountainous, and ecologically sensitive terrains. Hybrid-drive unmanned vehicles (HDUVs) present a transformative potential by integrating fuel-electric powertrains with autonomous navigation systems, enabling energy-efficient operations with minimal environmental impact. This review synthesises and critically analyses advancements in three critical domains: (*i*) dynamic modelling and chassis design for enhanced terrain adaptability, (*ii*) hybrid powertrain optimisation for reduced emissions and extended operational range, and (*iii*) the integration of unmanned systems for precision forestry tasks. By examining multi-body dynamics, power management strategies, and AI-driven navigation algorithms, we elucidate the role of HDUVs in improving operational efficiency while mitigating soil disturbance and carbon footprint. The review identifies prevailing research gaps and suggests that future work should prioritise the development of standardised testing protocols and foster cross-disciplinary collaboration to align HDUV development with EU biodiversity and climate objectives.

Keywords: hybrid-drive systems; precision forestry; sustainable forest management; unmanned ground vehicles

In response to intensifying ecological imperatives, optimising resource allocation and reducing operational costs in European forestry and grassland management have become strategic priorities. This focus is formalised in initiatives such as the European Forest Institute's research networks and the EU Forest Strategy 2030, which explicitly recognise forests as critical carbon sinks and vital economic resources (Muigg et al. 2020). These policy frameworks underscore a dual commitment to technological innovation and ecological preservation in sustainable land management. Traditional mechanised operations face compounded challenges in Europe's fragmented terrains – notably steep slopes and densely vegetated landscapes – where conventional tracked or wheeled vehicles often contribute to soil compaction, habitat fragmentation, and operational inefficiencies, while also struggling with limited accessibility (Dymov et al. 2022; Mykhailenko et al. 2024).

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Hybrid-drive unmanned vehicles (HDUVs) represent a promising technological solution to these limitations. By synergising internal combustion engines (ICEs) for extended mobility with electric propulsion for low-noise, high-precision tasks, HDUVs achieve adaptive power distribution across diverse forestry workflows. Empirical studies confirm their dual advantages: leveraging the endurance of fuel-based systems alongside the efficiency of electric drives to enhance energy conservation, environmental compatibility, and terrain adaptability (Dong et al. 2022). Crucially, HDUV power systems can dynamically adjust energy allocation in real-time, ensuring long-range transport capability via ICEs while enabling precise, low-impact operations through electric drives, even on steep and obstacle-rich terrain (Gao et al. 2025). This architecture concurrently mitigates the range limitations inherent in pure-electric systems under heavy loads and reduces emissions from conventional machinery (Redi et al. 2021), thereby aligning with the urgent demand for sustainable forestry technologies.

The autonomous capabilities of HDUVs further augment their operational value. Multi-sensor fusion and artificial intelligence (AI) algorithms facilitate centimetre-level positioning and robust path planning, while visual SLAM (Simultaneous Localisation and Mapping) ensures reliable obstacle avoidance and precision task execution in GPS-denied environments, such as under dense canopy cover (Guan et al. 2024). These features collectively address labour shortages in remote operations and minimise human exposure to hazardous working conditions.

This paper aims to provide a comprehensive and in-depth review of research progress on hybrid unmanned vehicles for complex forest and grassland terrains, focusing on three interconnected dimensions: dynamic characteristics, hybrid power systems, and unmanned system integration. By synthesising the latest research findings, this review elaborates on the technical features, key challenges, and innovative solutions within each dimension. Furthermore, it projects future development trends for HDUVs, anticipating their evolution towards greater intelligence and specialisation based on technological trajectories and industrial needs. The literature search for this review was conducted using major academic databases (e.g. Web of Science, Scopus, IEEE Xplore) and focused primarily on research from the past decade. The selection criteria prioritised studies relevant to vehicle dynamics, hybrid powertrains, and autonomous navigation in unstructured forest and grassland environments.

RESEARCH ON THE DYNAMICS OF FORESTRY AND GRASSLAND OPERATIONAL VEHICLES

Vehicles represent highly integrated systems whose stability, manoeuvrability, and comfort derive from the synergistic interaction of various subsystems, functioning as a unified operational entity (Da Lio et al. 2020; Gillespie 2021). The chassis subsystem exerts a particularly significant influence on overall vehicle dynamics (Skrickij et al. 2024), a critical consideration for European forestry and grassland operations where vehicles encounter complex terrains and multi-directional nonlinear forces. These challenging conditions demand exceptional dynamic performance. Consequently, vehicle design and research must:

(*i*) Characterise dynamic properties under operational stresses;

(*ii*) Investigate chassis-subsystem interactions and their collective impact on system dynamics;

(*iii*) Quantify nonlinear forces during operation to ensure stable and efficient performance in Europe's ecologically sensitive and topographically diverse landscapes.

Chassis design and analysis for European forestry applications. The evolution of European forestry machinery began in the late 19th century with the integration of mechanised elements into timber production. Initial operations utilised simple wooden-track systems and manually propelled vehicles (Zheng et al. 2021). Subsequent technological advancements and industrialisation drove significant innovation, as evidenced by specialised equipment from leading European manufacturers (Figure 1). Representative systems include:

- All-terrain utility vehicles (Benatti et al. 2022);
- Brush-cutting and vegetation management systems (Abilzhanuly et al. 2025);
- Timber forwarders and harvesters (Zheng et al. 2023);
- Forest surveillance and patrol platforms (Yu et al. 2023);
- Multi-functional terrain-adaptive systems (Rakhra et al. 2020).

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Figure 1. Types of typical forestry and grassland operational machinery

These vehicles face distinctive challenges in Europe's variable montane and forest ecosystems. Particularly in Alpine, Carpathian, and other upland regions – where conventional infrastructure coverage is limited – chassis systems require:

– Advanced dynamic response capabilities to handle slope instability (typically > 30% gradients);
– Enhanced torque distribution for obstacle negotiation;
– Minimised ground disturbance on sensitive soils (Liu et al. 2025).

Structural divergence from road vehicles arises from two fundamental factors (Wang 2020a):

(*i*) Terrain irregularity: Non-uniform load distribution on uncompacted, organically layered forest floors;
(*ii*) Operational specificity: Dynamic requirements for simultaneous locomotion and task execution (e.g. skidding, processing).

The design of a vehicle chassis for complex forest and grassland terrain must consider three key characteristics: (*i*) low ground pressure to prevent sinking into soft ground (Kulju, Ala-Ilomäki 2025); (*ii*) continuous contact between the wheels and the ground to ensure consistent traction (Wiberg et al. 2021); and (*iii*) good throughput, including stable operation on uneven and obstacle-riddled ground (Dong et al. 2025). To satisfy these requirements, wheeled chassis are often equipped with large tyres or multi-wheeled structures, coupled with highly flexible suspension systems to reduce ground pressure and adapt to terrain variations. Examples include John Deere's six-wheeled excavators and Swedish ROTTNE's eight-wheeled forest transporters, which utilise composite articulation technology to enhance agility and manoeuvrability (Arsenoaia et al. 2023). Furthermore, forestry vehicles frequently employ special low-ratio systems and transmissions to optimise engine power utilisation, particularly for soft terrain. Wheeled vehicles typically feature four-wheel drive for enhanced traction (Dymov et al. 2022), while two-wheel drive may be utilised on flat surfaces to improve efficiency and manoeuvrability (Grigorev et al. 2021).

Tracked chassis disperses pressure through wide and long tracks to ensure continuous ground contact, offering excellent obstacle-crossing and load-carrying performance (Dobretsov et al. 2020). Sun et al. (2021) designed the LY352J desert tracked transporter, which demonstrated superior desert passability and addressed the problem of sand subsidence through simulation and field tests.

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Lv et al. (2024) developed an omni-directional attitude-adjustable tracked chassis for agricultural machinery in hilly and mountainous areas, capable of automatically adjusting its attitude to maintain horizontal operation, thereby improving stability and efficiency. However, the complex structural design, large size, and weight of tracked undercarriages also introduce challenges such as high travelling resistance, limited operating speed, and lower efficiency, which can restrict their application in narrow spaces. To mitigate these issues, Caterpillar's Challenger 75E tractor employs rubber tracks to reduce weight and enhance performance, while Case's STX500 tractor utilises triangular rubber tracks and folded-waist steering technology to improve manoeuvrability and steering performance (Sun 2024).

The wheel-track combination chassis incorporates the advantages of both wheeled and tracked vehicles, offering a balance of speed and adaptability (Lin et al. 2024). In summary, these chassis designs exhibit various advantages and limitations in complex and variable forested terrain, and the selection of a specific type primarily depends on the operational objectives and specific application requirements.

Unlike traditional wheeled and tracked chassis, bionic chassis represents a newer type that has emerged in recent years, inspired by in-depth research on the locomotion methods of natural organisms. Examples include the Big Dog robot and SpouMini quadrupedal bionic robots (Shek et al. 2024), which can navigate freely in complex terrains such as hills and mountains, demonstrating strong balance and environmental adaptability. Their performance depends on (*i*) the number and layout of legs, (*ii*) joint flexibility and strength, and (*iii*) drive system performance (Wei et al. 2025a). In the future, with continuous technological development and the expansion of application scenarios, bionic chassis are anticipated to find broader development prospects in forest and grassland operational environments.

Vehicle dynamics modelling methods for forest and grassland operations. The complex terrain of forests and grasslands presents unique challenges, characterised by rugged landscapes, variable soil conditions, and dense vegetation cover, all of which severely test vehicle dynamics. To enhance the resilience and reliability of vehicles in these extreme environments, it is essential to thoroughly understand and accurately simulate their dynamic behaviour. Currently, fundamental theoretical research specifically focused on forest and grassland operational vehicles remains limited, with studies on vehicle travelling dynamics under such complex terrain being particularly scarce (Van, Tung 2024).

Dynamic models serve as core tools for studying the motion laws of a system under external forces, integrating multiple parameters such as force, energy, mass, inertia, and velocity, thereby providing a firm theoretical foundation for understanding vehicle motion characteristics. In the field of vehicle dynamics, vehicle motion is comprehensively described by six fundamental degrees of freedom: vertical, horizontal, and lateral translational motions, as well as rotational motions around the roll, pitch, and yaw axes (Zhai 2020).

In simplified models, vehicles are often treated as concentrated mass bodies with a centralised centre of gravity. However, in more detailed dynamic analyses, vehicles are modelled as multibody systems, particularly by considering wheels as independent unsprung masses. This approach is crucial for accurately capturing vehicle dynamic responses. The focus of vehicle dynamics research lies in controlling these degrees of freedom to achieve desired responses to operational inputs and ground conditions. For instance, horizontal forces directly influence the vehicle's acceleration/deceleration performance and traction characteristics, while vertical motion is closely related to ride comfort and driving stability (Zhou et al. 2023). As illustrated in Figure 2, vehicle models can be categorised into various degrees-of-freedom systems, such as two-degree-of-freedom (Chang 2022), three-degree-of-freedom (Zhu et al. 2022a), and seven-degree-of-freedom (Zhai et al. 2022) models.

Therefore, the study of dynamic characteristics of forestry-grassland operational vehicles is a complex yet essential topic. Research from related fields, such as planetary rovers (Hu et al. 2024), heavy all-terrain vehicles (Mo et al. 2025), and all-terrain articulated tracked vehicles (Dong et al. 2017), can provide valuable references for the dynamic modelling and optimisation of forestry-grassland operational vehicles. Future research should further concentrate on the complex interactions between vehicles and terrain, nonlinear material properties of tyres, and the dynamic response of suspension systems to foster continuous advancement in forest and grassland operational vehicle technology.

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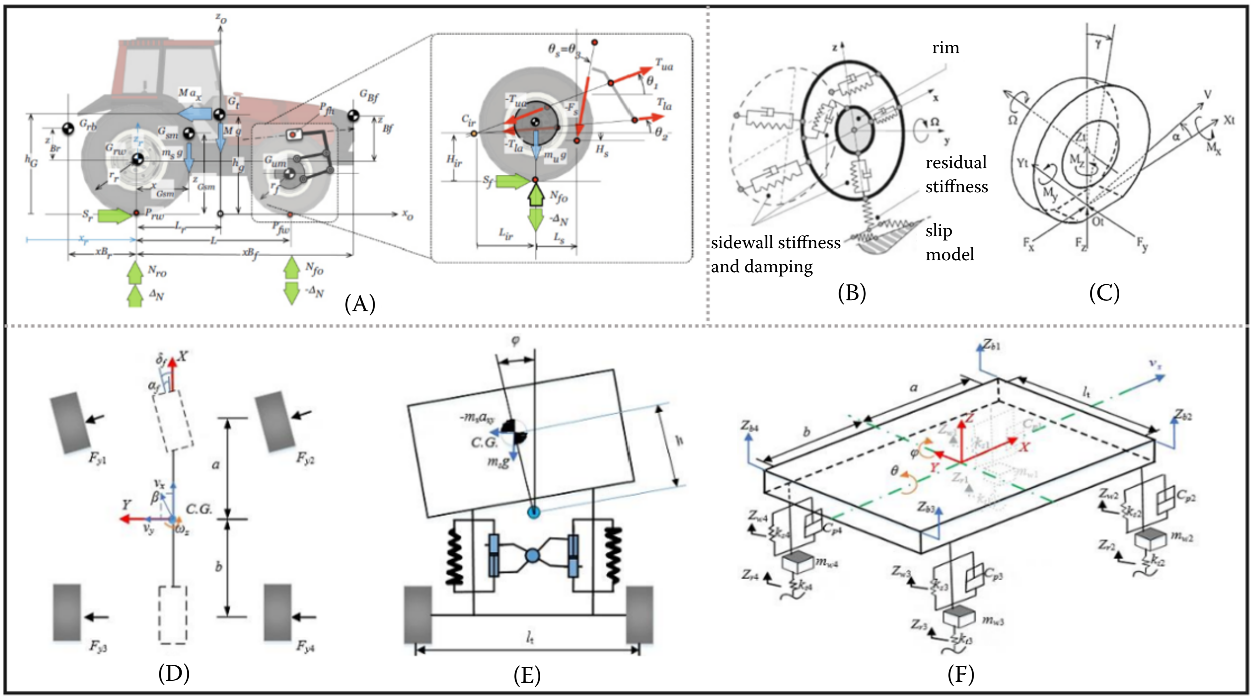

Figure 2. Dynamic modelling of forestry-grassland operational vehiclesv

Numerous open-source software libraries and commercial software packages are available for modelling multi-body dynamics. Well-known open-source dynamics simulation software includes ODE, Bullet, SIMBODY, and RBDL, while the commercial field features prominent products such as ADAMS, RecurDyn, SIMPACK, and SAMCEF (Lai et al. 2023). For example, Hu et al. (2020) proposed a wheel-track composite all-terrain vehicle platform and verified its ability to adapt to complex terrain through finite element analysis and dynamics simulation. Additionally, many laboratories have developed specialised dynamics simulation software for specific research topics. In the process of dynamics modelling and solving, each method demonstrates unique advantages, and no single model is universally superior. Typically, researchers distinguish algorithms based on modelling speed and solving efficiency. However, in practice, various modelling methods are influenced by programming proficiency and the programming language used, leading to differences in computational efficiency. This variation in efficiency, which subsequently affects solution time, has resulted in limited direct evaluations of the efficiency of distinct modelling methods in the literature.

HYBRID POWERTRAINS FOR FORESTRY AND GRASSLAND OPERATION VEHICLES

In recent years, continuous advancements in vehicle electrification have led to remarkable improvements in emissions within the road transport sector. However, concurrently, non-road mobile machinery (NRMM) is increasingly recognised as a significant source of pollution, and its emission problems cannot be overlooked. Consequently, many NRMM manufacturers are actively pursuing innovative alternatives to standard combustion engine drive systems. Hybrid-electric architectures are garnering attention due to their significant advantages in enhancing overall machine efficiency. By optimising the degree of hybridisation for specific work cycles, these architectures can reduce the amount of pollutants produced per unit of work, thereby achieving a better balance between environmental protection and operational efficiency.

Hybrid powertrain types for forestry and grassland operations vehicles. Powertrain design is central to the development of hybrid chassis, as its configuration and parameters directly influence the overall performance of the hybrid logging machine. Based on the power transmission mechanism, hybrid power systems are primarily categorised into

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series, parallel, and power-split (sometimes referred to as combined) types (Husain 2021).

As shown in Figure 3A, the driving force in a series-type system originates entirely from the electric motor. The system generates electrical energy by using an engine to drive a generator, which in turn powers the motor to output mechanical energy for vehicle propulsion. Excess electrical energy can be stored in a battery to extend the driving range. Since the engine is not mechanically connected to the drive wheels, this system is often considered suitable for complex roads and large vehicles operating at moderate speeds (Dong et al. 2022). The parallel-type system, depicted in Figure 3B, allows both the engine and the electric motor to provide power directly to the wheels. When the required driving power is less than the engine output, or during vehicle deceleration and braking, the motor can act as a generator to recharge the battery. This system permits the use of smaller, less powerful engines, aiding in reducing vehicle size and cost (Yang et al. 2025). The power-split or combined system, illustrated in Figure 3C, incorporates characteristics of both series and parallel systems. Its operating mode can be flexibly adjusted based on vehicle operating conditions, with series mode often dominating at low speeds and parallel mode at high speeds. The hybrid system can leverage the advantages of both modes, optimise working conditions, and improve energy utilisation, but it tends to be structurally more complex and costly, with relatively fewer current vehicle applications (Zhu et al. 2022b).

Hybrid power structures are characterised by their diverse forms, and their applicable conditions and ranges vary significantly, as summarised in Table 1. Among the three prevalent systems, the series hybrid configuration offers several distinct advantages:

(*i*) The series type can operate in pure electric mode under most working conditions, which is more challenging for parallel and power-split types, and typically utilises a larger battery capacity.

(*ii*) During braking, series-type systems generally allow for higher energy recovery efficiency due to the direct connection between the drive motor and wheels.

(*iii*) The series type is often deemed more suitable for complex road conditions and low-speed operation of heavy vehicles, such as those operating on steep forest and grassland terrain, making its design particularly relevant for these applications.

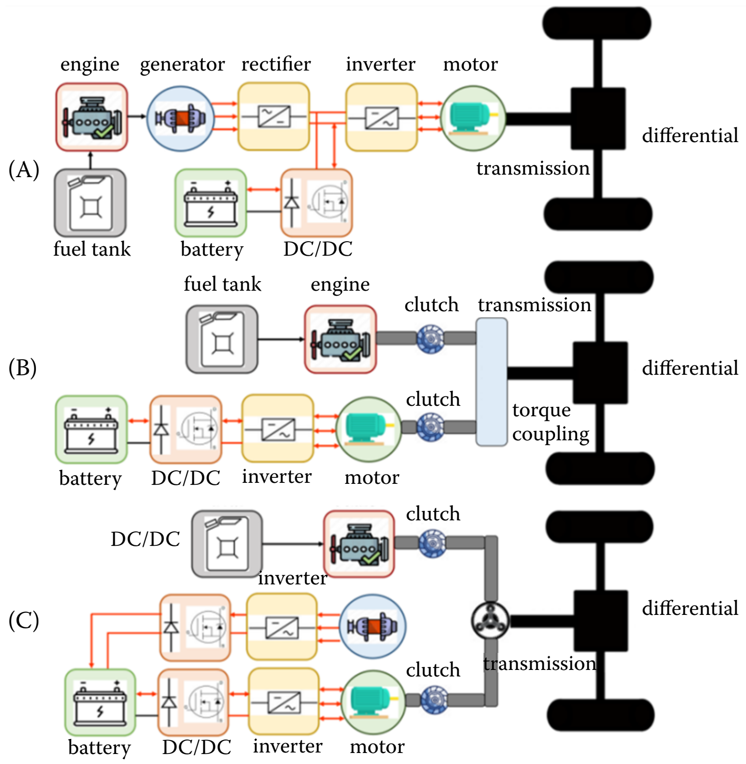

Figure 3. Hybrid power system

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Table 1. Comparative analysis of three hybrid electric propulsion topologies

Item	Series type	Parallel type	Hybrid
Structural characteristics	Direct connection between engine and generator.	The engine is connected to the generator through a coupler.	Both parallel and series systems are available.
Advantages	Greater freedom (space layout advantage), zero-emission operation, simple structure, improved economy.	Low cost and high reliability.	Combines the advantages of both series and parallel systems.
Disadvantages	Higher energy loss (multiple energy conversions), single structure.	Difficult to arrange the entire vehicle, poor stability, high voltage must be maintained to improve efficiency.	High cost, complex structure, requires high technology, difficult to control.
Applicable conditions and models	Adapt to complex road conditions, large vehicles, such as heavy buses, trucks and locomotives, etc.	Suitable for small and medium-sized vehicles, highway driving.	Suitable for complex road conditions, light vehicles. High cost makes them less commonly used.

In the field of forestry and grassland operations, the application of commercial hybrid products remains relatively scarce. The development history and technological progression of hybrid agricultural and forestry tractors, as representative products in this domain, have thus become a focus of research attention. As early as 2009, a Belarusian company pioneered the launch of the 3023 hybrid tractor, a landmark product signifying an important step in tractor electrification. This tractor utilised a series hybrid architecture centred around a 220 kW diesel engine driving a generator, which subsequently supplied power to a 183 kW electric motor and a 55 kW PTO (power take-off) motor. Notably, this design lacked an energy storage device (battery), with all power derived directly from the diesel engine. While this solution facilitated electrification of power conversion, it left considerable room for improvement in terms of energy use efficiency and operational flexibility (Hu et al. 2022).

Subsequently, in 2013 and 2015, John Deere's 6210 RE tractor and CLAAS's ARION 650 Hybrid tractor adopted similar series hybrid architectures, further advancing the development of tractor electrification technology (Mocera, Somà 2022). The introduction of these products not only validated the feasibility of series hybrid architectures in the tractor field but also provided valuable practical experience for subsequent technological innovations.

However, the limitations of series hybrid architectures gradually became apparent. In response, the Italian company Carraro introduced the Carraro Ibrido hybrid tractor concept in 2018, a design employing a parallel architecture to achieve greater flexibility and efficiency in the powertrain. Equipped with a 55 kW diesel internal combustion engine, a 20 kW electric motor, and a 25 kWh battery pack, the tractor could operate flexibly in three modes: conventional engine-only, hybrid, and purely electric. This innovation not only improved the tractor's energy efficiency but also significantly enhanced its adaptability across various operating environments, marking another important advancement in tractor electrification technology (Borghi 2023).

Caterpillar announced a breakthrough in its off-road work vehicle program in 2024. The company developed a hybrid heavy-duty diesel system incorporating a downsized diesel engine (30% less displacement) with a front-end accessory drive, and introduced advanced technologies such as high-speed flywheel energy storage, SuperTurbo mechanical turbocharging, and an electric genset. The design combines a downsized, heavy-duty diesel engine with sophisticated combustion technology to effectively recycle and utilise exhaust gas energy. Simultaneously, by integrating mechanical and electrical energy recovery mechanisms, the system is projected to reduce fuel consumption by 15–20%, fully demonstrating the signifi-

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cant potential of hybrid technology to improve energy efficiency and reduce emissions in off-road applications.

In summary, the development of hybrid technology in tractor electrification has undergone a transition from series to parallel architectures, achieving notable improvements in energy efficiency, flexibility, and adaptability. Future advancements are expected to see hybrid vehicles playing an increasingly vital role in the forestry and grassland operations sector, contributing to the goals of green and sustainable machinery development.

Energy management methods for hybrid power systems. Hybrid vehicles are complex electromechanical-chemical systems whose potential for fuel economy gains and emission reductions is heavily dependent on the powertrain topology and the selection of an effective Energy Management Strategy (EMS). The primary goal of an EMS is to efficiently distribute power from various sources within the driveline by selecting appropriate operating modes. These goals typically include improving fuel economy, reducing emissions, ensuring drivability, and maintaining the state of charge (SOC) and longevity of the energy storage system, all while adhering to system constraints.

Over the past decade, numerous studies have been published on EMS applications in hybrid vehicles. While several classification schemes exist, a generally accepted categorisation distinguishes three primary types: rule-based, optimisation-based, and learning-based strategies, as outlined in Table 2.

Rule-based methods can be further subdivided into deterministic rule-based EMS and fuzzy logic EMS. These strategies operate based on a set of predefined rules, typically formulated using engineering intuition and analysis, without requiring prior knowledge of the entire driving cycle (Muthyala et al. 2024). In contrast, optimisation-based methods are classified into global (offline) and real-time (online) optimisation, depending on the extent of driving condition information used (Saiteja, Ashok 2022). Generally, optimisation-based methods have attracted significant research attention due to their potential for higher efficiency. Among offline optimisation methods, dynamic programming, Pontryagin's Minimum Principle, and meta-heuristics (e.g. genetic algorithms, particle swarm optimisation) are extensively used for global optimisation search (Ding et al. 2022). Meanwhile, Equivalent Consumption Minimisation Strategy (ECMS) and Model Predictive Control (MPC) are widely employed as online optimisation methods. Learning-based methods demonstrate considerable potential, leveraging recent advances in machine learning and artificial intelligence for network training using online or historical data (Ganesh, Xu 2022). It is noteworthy that a powerful EMS often combines various techniques to form an integrated strategy for improved overall fuel economy and performance.

In summary, the current research challenges for hybrid power systems in forest and grassland operation vehicles include:

(*i*) Multifunctional and adaptive design: A single machine may encounter a wide variety of complex and changing work scenarios during its lifespan. Designing a versatile architecture that efficiently meets all these diverse requirements is extremely challenging (Hou 2024). The complex terrain and varied duties in forest and grassland environments make it particularly difficult to design a hybrid vehicle that operates efficiently and adapts robustly across all potential scenarios.

(*ii*) Cost-benefit considerations: While electric technologies can demonstrate benefits in reducing the total cost of ownership over the machine's life, oversized electric components (motors, batteries) can substantially increase the initial machine cost. Manufacturers must find the optimal trade-off between performance, functionality, and economics, especially in selecting the hybrid drivetrain configuration and component sizing (Wang et al. 2025).

(*iii*) Energy management and charging efficiency: Developing an efficient, reliable, and robust energy management system is crucial for hybrid vehicles. However, designing control strategies that maximise energy efficiency (including charging efficiency, if applicable) and minimise operational costs, while ensuring stable and reliable operation in complex and unpredictable environments, remains a significant research challenge.

Hybrid technology entails the integration of several disciplines, including power electronics, battery management, and internal combustion engine technology. Fostering innovation across these technical fields to simultaneously enhance performance and reduce the cost of hybrid forest and grassland operation vehicles is a crucial direction for current and future research.

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Table 2. Advantages and disadvantages of EMS control methods for forest-grass terrain

Type of methods	Control strategy	Advantages	Challenges (forest-grass terrain)
Rule-based approach	Decision control (Sun et al. 2025)	– Simplicity (if-then structure) (Zhou et al. 2020)	– Difficult to formulate rules for complex working conditions in forest and grass
	Fuzzy control (Suhail et al. 2021)	– Comparable to human reasoning – Use of linguistic models – Apply simple math to nonlinear, integrated or even complex systems (Mazouzi et al. 2024) – High precision – Fast operation	– Control parameters required for different driving situations are difficult to calibrate – Exponentially increasing number of rules with more fuzzy levels – Difficult to maintain real-time response
Optimisation-based approach	Dynamic planning (offline) (Chen et al. 2023)	– Global optimisation – Wide applicability – Suitable for dealing with complex problems (Yin et al. 2025)	– Difficult to obtain driving cycle information in advance – Curse of dimensionality, computationally expensive
	Game theory (offline) (Cheng et al. 2020)	– Synthesise trade-offs for conflicting objectives – Consider driving behaviour in EMS (Li 2024)	– Curse of dimensionality, computationally expensive – Cannot cover the full range of scenarios
	MPC (online) (Peicheng et al. 2022)	– Adaptive and predictive capability (Wang, Song 2024) – Solutions that approximate the global optimum with less online computation (Hu et al. 2025)	– Requires preview of driving patterns, terrain/future driving information – Highly model-dependent
	Sliding mode control (online) (Yang et al. 2024)	– Robust to parameter variations and uncertainties (Wang et al. 2020) – Fast system response	– Limitations on nonlinear systems – Strong dependence on the paradigm
Learning based approach	Reinforcement learning (Du et al. 2022)	– No model control – Some generalisation capability (Cao et al. 2025) – Suitable for complex dynamic environments (Tang et al. 2025)	– Data set preparation consumes time – Rewards signal delays and inaccuracies – Sensitive to external disturbance
	Neural networks (Chen et al. 2022)	– Powerful nonlinear mapping capability (Zhang et al. 2025) – Adaptive (Wu et al. 2024) – Suitable for multi-input, multi-output systems	– Requires large amount of training data – Long learning time – Output results are difficult to interpret

UNMANNED VEHICLE SYSTEM FOR FOREST AND GRASS OPERATION

Currently, the vast majority of forest and grassland operation vehicles still rely on manual operation, which places extremely high demands on the operator's skill and concentration. In complex and dynamic forest environments, the operator must continuously monitor the surroundings and make rapid, accurate decisions to ensure driving precision and safety, a task that is undoubtedly challenging and prone to fatigue. Given the limitations and stringent requirements of manual operation, intelligent and unmanned equipment has gradually emerged as a key enabler for modernising forest and grassland machinery, indicating a future main-

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stream development direction towards unmanned vehicles (Wang 2020b; Ruetz et al. 2024).

Unmanned vehicles integrate advanced technologies from disciplines such as artificial intelligence, geographic information science, navigation technology, sensor systems, and communications, attracting significant research interest in recent years (Liu et al. 2021; Dinelli et al. 2023; Wei et al. 2025b). This increased attention is driving the development of more autonomous and intelligent vehicles capable of operating in forest and grassland environments, with the potential to substantially improve operational efficiency and reduce resource consumption.

Autonomous navigation is a fundamental prerequisite for unmanned operational vehicles to perform various tasks in forest and grass environments (Liu et al. 2021). An efficient navigation system leverages environmental and positioning information acquired by sensors to guide the vehicle accurately along predefined paths or towards targets, enabling precise task execution (Duan 2023). However, the complexity, unstructured nature, and inherent disorder of forest and grassland environments, coupled with prevalent noise sources and disturbances, make autonomous navigation particularly challenging (Li et al. 2022). These challenges stem from inconsistencies in environmental structure, variations in vegetation shape and colour, terrain surface unevenness, and fluctuating lighting conditions (Yin 2023). Furthermore, hardware limitations such as actuator and controller noise, finite battery capacity, wheel slippage, and inaccuracies in sensor measurements can further degrade navigation performance (Nowakowski, Kurylo 2023).

Consequently, designing a navigation system that is accurate, robust, and adaptable to complex forest and grass environments is essential for automating forestry and grassland operations. To address this need, researchers have rapidly developed and proposed various navigation methodologies, leveraging technologies including Global Navigation Satellite Systems (GNSS) (Lee et al. 2023), Light Detection and Ranging (LiDAR) (Henrich et al. 2024), Inertial Measurement Units (IMUs) (Moghadam et al. 2023), Ultra-Wideband (UWB) (Zheng et al. 2025), and vision-based sensors.

Among these, GNSS-based autonomous positioning has become one of the most widely used solutions due to its global coverage and potential for centimetre-level accuracy (with Real-Time Kinematic – RTK corrections). GNSS enables continuous position tracking of unmanned vehicles in a global coordinate system, significantly enhancing operational resource scheduling and real-time environment awareness in open grassland settings. However, in unstructured forestry terrain, its positioning stability is constrained by multiple environmental factors: satellite signals are susceptible to attenuation and multipath effects caused by dense canopy cover, as well as atmospheric disturbances, leading to degraded accuracy or even temporary signal loss (Mo 2020). Rybansky et al. (2023) investigated the accuracy of a GNSS receiver for off-road vehicle navigation in a typical temperate forest in Central Europe. They selected two locations and accurately marked reference elements such as trees and vehicle routes using a rangefinder to assess navigation accuracy. The study quantified positioning accuracy and positional deviation (the difference between the receiver's recorded position and the actual measured position). Results indicated that GNSS devices performed reasonably well for approximate vehicle localisation, particularly in sparse woodland environments. However, accurately determining the precise relative position between the vehicle and trees in dense forest areas proved more challenging.

In contrast, LiDAR sensors provide high-resolution, wide field-of-view ranging data, offering robust capabilities for target detection and localisation (Wei, Chen 2024). By constructing real-time 3D point cloud maps and employing Simultaneous Localisation and Mapping (SLAM) algorithms, LiDAR can enable centimetre-level localisation for unmanned vehicles in GPS-denied, unstructured forest environments. To evaluate the utility of SLAM-assisted trunk mapping for forest resource inventory, Tang et al. (2015) conducted experiments using a small mobile LiDAR system mounted on an FGI ROAMER R2 vehicle. They traversed both open and dense forest areas, comparing three navigation approaches: GNSS-only, GNSS coupled with an IMU (GNSS + IMU), and LiDAR SLAM coupled with an IMU (SLAM + IMU). The results demonstrated that in open areas, the SLAM algorithm was less feasible due to fewer detectable features and the higher reliability of GNSS signals. However, in the dense forest region, the SLAM + IMU technique provided 38% higher accuracy than the GNSS + IMU approach.

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For autonomous navigation under heavy canopy cover, Li et al. (2020) utilised a real-time localisation algorithm based on LiDAR Odometry and Mapping (LOAM) for tree mapping. A schematic of the LiDAR scanner's mounting on the Komatsu Forest 931.1 harvester is provided in Figure 4, including an overall view (A) and a close-up (B). The algorithm constructs a unique 2D topological map from point cloud data and establishes optimal relationships between global and local topologies. Experimental results demonstrated that their method achieved a localisation accuracy of approximately 0.3 m (with a standard deviation of 12 cm) at speeds up to 0.5 m·s−1 while maintaining real-time data processing capability.

The AgRob V18 forest robot was developed for forest biomass capture. Equipped with a modular sensor suite for perceiving its surroundings, its tracked, diesel-engine-driven mobility system caused significant vibration, adversely affecting IMU data. Consequently, researchers investigated several autonomous localisation and navigation methods, including standard LOAM for structured environments, A-LOAM (a C++ implementation optimised for speed), and LeGO-LOAM (Lightweight and Ground-Optimised LiDAR Odometry and Mapping). Experimental results indicated that LeGO-LOAM delivered the best performance among the three methods under these challenging conditions (Shan, Englot 2018).

Pierzchała et al. (2018) employed a Superdroid 4WD IG52 DB robot in a semi-structured, flat, sparsely vegetated forest in Norway. Using a 3D graph-based SLAM method, they successfully identified tree trunks and estimated diameter at breast height (DBH). Given the low density of obstacles in the test environment, the proposed method achieved an average DBH estimation error of 2 cm and an average tree localisation error of 0.0476 m.

Despite its advantages, the high cost of high-performance LiDAR sensors can limit their large-scale deployment on forest and grassland operation vehicles. Machine vision, as an autonomous navigation and localisation method, is emerging as a viable candidate to complement or even replace LiDAR in some applications, owing to its relatively lower cost and continually improving accuracy (Chen 2023; Yang et al. 2023). Vision-based methods are characterised by high intelligence, a wide detection range, non-contact measurement, and rich informational content, providing users with extensive data about the vehicle's surroundings and enabling the acquisition of features relevant to navigation (Zhu et al. 2022c). As early as 1997, Gerrish's research demonstrated the capability of monocular vision systems to achieve high navigation accuracy under varying light and speed conditions, particularly for stable long-distance navigation when approaching crop rows. By 2022, Ruangurai et al. constructed a planter navigation system using machine vision technology, achieving high-precision control of row spacing and direction by combining Hough transform and Principal Component Analysis (PCA).

Figure 4. (A) Komatsu Forest 931.1 forest harvester (the LiDAR scanner is marked by a red circle in the front of the windshield of the cabin); (B) a close-up of the LiDAR scanner (Li et al. 2020)

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In the context of forest and grassland terrain perception, vision-based techniques are primarily categorised into two main approaches: traditional feature detection and machine learning-based methods (Zeil 2023). Feature detection algorithms identify drivable areas or obstacles based on features like colour, texture, and edges within the image. Common strategies include colour feature segmentation, image segmentation combining Otsu's method and Bayesian decision theory, and moving obstacle detection using optical flow methods (Yu et al. 2025). However, these strategies can be susceptible to interference from environmental factors such as varying illumination, shadows, and precipitation.

In contrast, machine learning algorithms can automatically learn and adapt to environmental features by training parameterised models, often demonstrating greater robustness and environmental adaptability. Common machine learning approaches applied include superpixel segmentation combined with k-Nearest Neighbour (k-NN) classification, multilayer perceptron models, Fully Convolutional Network (FCN) for semantic segmentation, and encoder-decoder architectures like SegNet (Gao 2020; Zhang et al. 2023; Li et al. 2024).

At the technical challenge level, automatic navigation for unmanned vehicles must contend with the difficult problem of complex and highly variable forest and grassland terrain. This includes diverse and ill-defined drivable areas, undulating slopes, and the presence of both dynamic and static obstacles. Traditional feature detection methods are often prone to failure or inaccuracy under challenging lighting and complex background conditions. Meanwhile, machine learning-based techniques, particularly deep learning, place higher demands on computational resources, sensor quality, and the design of algorithmic models capable of learning complex, high-level feature representations. Although data augmentation techniques can help mitigate the negative impact of environmental variations on model performance, most current state-of-the-art models rely on supervised learning paradigms, requiring substantial amounts of manually labelled image data for training, which is time-consuming and costly. Furthermore, while visual sensors capture rich information, their performance remains vulnerable to adverse lighting conditions (e.g. low light, glare) and poor weather (e.g. fog, rain, snow). Therefore, future research needs to focus on developing more robust and efficient deep learning models, potentially leveraging semi-supervised or self-supervised learning to reduce dependency on large labelled datasets, and effectively addressing the challenges of real-time performance and generalisation in unstructured outdoor environments.

CONCLUSION

Research on HDUVs for complex European forest and grassland terrain represents a cutting-edge interdisciplinary frontier integrating critical technological domains: vehicle dynamics, hybrid propulsion systems, and autonomous navigation (Figure 5). This field demands a systematic analysis of intrinsic mechanisms and the resolution of pivotal scientific and technical challenges to achieve efficient, stable, and intelligent HDUV operations in Europe's ecologically sensitive and topographically demanding montane landscapes.

Regarding dynamics, research focuses on the design of vehicle chassis structures and suspension systems tailored to the specific requirements of complex European forest and grassland terrains, aiming to enhance vehicle passability, stability, and minimise soil impact. Concurrently, in-depth investigation into vehicle traction control, brake force distribution, and other dynamic aspects is essential to ensure safe and reliable operation in these challenging environments.

Hybrid power technology forms a foundational element of HDUV research. By optimising powertrain architecture design and developing sophisticated energy management strategies (EMS), the fuel economy, operational range, and overall efficiency of the vehicle can be substantially improved. Particularly in forestry and grassland operations, where HDUVs must frequently switch between diverse terrains and working modes, realising intelligent mode selection and efficient coordination between power sources remains a key challenge.

In the domain of unmanned system control, research concentrates on enabling robust autonomous navigation, reliable obstacle avoidance, and effective remote monitoring functionalities. In complex forest and grassland terrain, unmanned vehicles depend on high-fidelity environment perception systems and advanced, real-time path planning algorithms to achieve autonomous navigation

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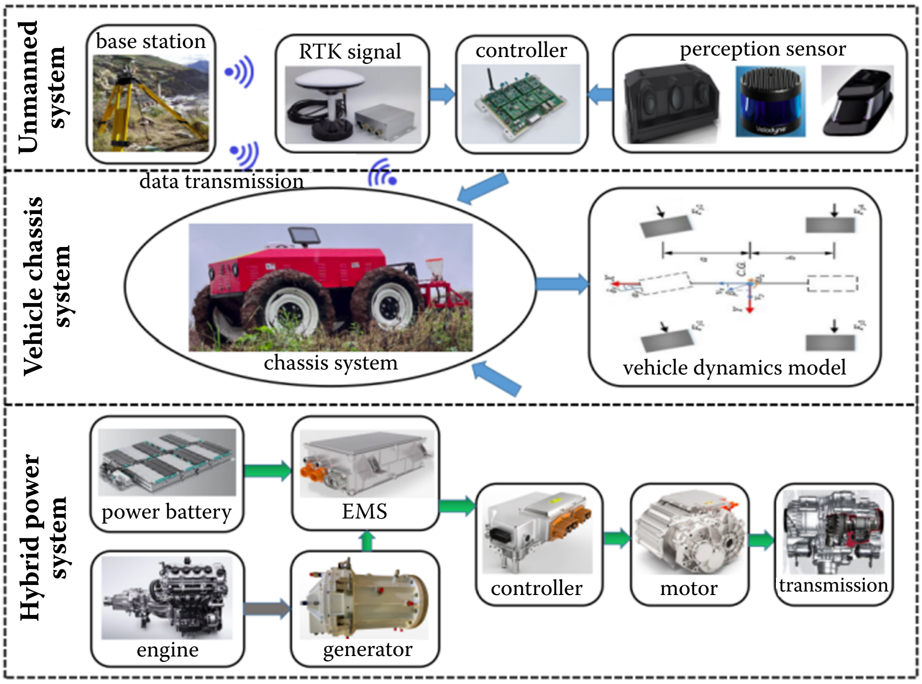

Figure 5. Hybrid electric unmanned system for forestry operations in vegetated complex terrain

RTK – Real-Time Kinematic; EMS – Energy Management Strategy

and safe obstacle avoidance. Simultaneously, remote monitoring systems are crucial for providing operators with real-time data on vehicle status and operational progress, enabling informed decision-making and oversight.

To synthesise the core findings of this review, Table 3 summarises the key insights, prevailing challenges, and recommended future research directions for each critical technological domain.

In conclusion, the development of HDUVs for complex forest and grassland terrains involves multiple intertwined technological areas, necessitating strong interdisciplinary collaboration and innovation. By conducting in-depth research on these key technologies and addressing the associated scientific challenges, the application and advancement of HDUVs can be significantly accelerated. In the future, with continuous technological progress and

Table 3. Synthesis of research findings, challenges, and future directions for HDUVs

Technological domain	Key findings	Current challenges
Vehicle dynamics & chassis design	Advanced chassis (articulated wheeled, rubber-tracked, wheel-track composite) are crucial for passability and low ground pressure.	Trade-offs between mobility, stability, speed, and complexity persist. Accurate multi-body dynamics modelling for nonlinear terrain forces remains difficult.
Hybrid powertrains & energy management	Series hybrids are suitable for complex, low-speed operations; parallel/hybrid systems offer flexibility. Optimisation-based EMSs outperform rule-based ones.	Achieving multifunctional design adaptability, cost-effectiveness, and robust EMS for highly variable forestry duty cycles.
Unmanned systems & autonomous navigation	Sensor fusion (LiDAR-SLAM, Vision) is essential for reliable GPS-denied navigation, achieving centimetre-level accuracy in structured patches.	Ensuring robustness against environmental variations (light, weather, canopy density), high sensor costs, and data processing requirements for real-time decision-making.

HDUV – hybrid-drive unmanned vehicle; EMS – Energy Management Strategy

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innovation, hybrid unmanned vehicles are poised to play an increasingly vital role in forestry and grassland operations, providing powerful technical support for the sustainable management and conservation of these vital natural resources.

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