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RESEARCH ARTICLE | JULY 08 2026

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AIP Conf. Proc. 3496, 080001 (2026)
https://doi.org/10.1063/12.0044449

View Online Export Citation

23 July 2026 13:58:51

AIP Publishing

Conceptual Framework for Maneuverability Control of Mobile Aerodrome Support Systems as Nonholonomic Platforms

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Abstract. This paper presents a conceptual framework for maneuverability control of mobile aerodrome support systems, modeled as nonholonomic platforms with both real and virtual kinematic steering constraints. These systems – including tow tractors, mobile power units, and technical service vehicles – operate in spatially constrained airfield environments, where precise maneuvering and adaptive control are critical for safe and efficient operations. A mathematical model is developed to formalize the trajectory control process under nonholonomic constraints, enabling accurate path planning and real-time correction. The proposed control system architecture integrates trajectory generation algorithms with adaptive feedback mechanisms, allowing the platform to respond dynamically to environmental changes and obstacle configurations. Special emphasis is placed on the use of virtual steering constraints, which simulate additional degrees of freedom without requiring physical modifications to the vehicle's mechanical structure. This approach enhances maneuverability and flexibility, particularly in tight operational zones. Experimental scenarios demonstrate the effectiveness of the proposed system in improving positioning accuracy, reducing trajectory correction frequency, and ensuring safe obstacle avoidance. The results are applicable to the development of intelligent ground support systems for aviation, contributing to increased automation, operational safety, and functional adaptability in high-density airfield traffic conditions.

Keywords: nonholonomic systems; mobile aerodrome support platforms; trajectory optimization; kinematic constraints; control algorithms; path planning; ground vehicle dynamics.

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INTRODUCTION

Modern aerodrome operations increasingly rely on mobile ground support systems such as tow tractors, power units, and technical service vehicles to ensure efficient aircraft handling and maintenance. These platforms often operate in spatially constrained environments, where precise maneuverability and adaptive control are critical to maintaining safety and operational continuity [1].

Due to their mechanical design, many of these vehicles exhibit nonholonomic motion constraints – limitations that prevent arbitrary movement in all directions [2]. Traditional control methods are often insufficient for handling such constraints, especially in dynamic scenarios involving obstacle avoidance, tight turns, and trajectory corrections near aircraft or infrastructure [3].

The problem of maneuverability control for nonholonomic mobile platforms has been extensively studied across various control paradigms. Traditional approaches such as proportional-integral (PI) and proportional-integral-derivative (PID) controllers remain widely used due to their simplicity and low computational cost. However, they exhibit limited adaptability and poor performance in constrained environments typical of aerodrome operations [4].

Modern Automotive Industry, Transport and Road Infrastructure '2025
AIP Conf. Proc. 3496, 080001-1–080001-8; https://doi.org/10.1063/12.0044449
Published under an exclusive license by AIP Publishing. 978-0-7354-5376-0/$30.00

Inverse kinematic modeling has been proposed to address trajectory tracking under nonholonomic constraints. While effective in structured environments, these methods are sensitive to sensor noise and lack robustness in dynamic scenarios [5]. Linear Quadratic Regulators (LQR) offer improved stability and trajectory optimization for linearized models, but their applicability to strongly nonlinear nonholonomic systems is limited [6].

Sampling-based planners such as Rapidly-exploring Random Trees (RRT) have demonstrated high flexibility and precision in trajectory generation, particularly when integrated with kinematic constraints [7]. Model Predictive Control (MPC) has emerged as a powerful technique for real-time trajectory optimization. Recent work by Rosenfelder et al. [8] presents a comprehensive MPC framework tailored to nonholonomic systems, incorporating sub-Riemannian geometry and non-quadratic cost functions for improved trajectory stabilization and real-time applicability.

Furthermore, deep learning-based control strategies have shown promise in handling complex maneuvering tasks. Neural networks trained on dynamic datasets can generalize across scenarios and offer high adaptability, though they require significant computational resources and training data. Recent reviews also highlight the effectiveness of deep reinforcement learning algorithms in navigating crowded and dynamic environments, where traditional rule-based systems often fail to adapt in real time [9].

These developments highlight a shift from rule-based control to data-driven and predictive frameworks, enabling more intelligent and flexible maneuverability solutions for nonholonomic ground support systems.

This study proposes a conceptual framework for maneuverability control of mobile aerodrome support systems, treating them as nonholonomic platforms with both real and virtual kinematic steering constraints. The integration of virtual constraints enables the simulation of complex maneuvers without physical modifications to the vehicle's structure, offering a cost-effective and scalable solution.

The paper presents a mathematical model that formalizes trajectory planning and correction under nonholonomic conditions. It also introduces a modular control system architecture capable of adapting to changing operational contexts. The proposed approach aims to enhance positioning accuracy, reduce maneuvering time, and improve overall safety in high-density airfield environments.

RESEARCH MATERIALS AND METHODS

The quality and completeness of ground aviation technical support (GATS) operations for aircraft depend on a range of operational and tactical factors, including mobility, standardization, reliability, timeliness, flight safety assurance, average movement speed, the ability to operate in spatially constrained areas, and the capability to maneuver in reverse [1, 2].

Modern armed forces increasingly adopt modular design principles for GATS platforms, enabling flexible deployment and improved adaptability to diverse operational conditions [10]. However, the widespread use of dual-axle trailers with low-profile wheels in modular vehicle configurations does not fully meet the tactical-technical and operational requirements of military ground support equipment, particularly under the conditions of Ukrainian airfields and during relocation to reserve or forward-operating bases.

Specifically, such trailer-based modular systems are unsuitable for precise reverse maneuvering near aircraft, within shelters and hangars, or in confined logistics zones such as depots and vehicle parks – where flight safety and spatial precision are critical. These limitations hinder the execution of logistical operations in constrained environments and compromise the overall effectiveness of GATS systems.

This research addresses the need to improve the tactical and operational characteristics of ground support vehicles by proposing a novel multi-module GATS platform architecture based on single-axle trailers. The study focuses on developing a control framework that ensures stable and accurate maneuverability during reverse motion toward aircraft, thereby enhancing positioning precision, operational safety, and adaptability to airfield constraints.

In the theory of wheeled transport systems, which includes ground aviation technical support platforms, steering and maneuvering behavior is fundamentally influenced by the Ackermann steering geometry – a globally recognized principle originally patented in the 19th century. In its modern formulation, the Ackermann principle is expressed through a geometric relationship that defines the angular coordination between the left and right steering wheels during a turn [11].

$$ctg\gamma_L - ctg\gamma_R = \frac{B}{L}, \tag{1}$$

where γ_L is the steering angle of the left wheel; γ_R is the steering angle of the right wheel; B denotes the track width (distance between the steering pivots of the left and right wheels); L represents the wheelbase (distance between the front and rear axles).

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The Ackermann geometry ensures that all wheels of a vehicle follow concentric circular paths during a turn, thereby minimizing tire slip and improving maneuverability. This principle remains a foundational element in the design of steering systems for both civilian and military ground vehicles, particularly in applications requiring precise control in constrained environments such as airfields, shelters, and hangars.

Ground aviation technical support (GATS) platforms equipped with wheeled chassis can be formally represented as mechanical systems of interconnected rigid bodies, in accordance with the principles of theoretical mechanics [12]. Traditionally, the primary objective of theoretical mechanics is considered to be the derivation of the law of motion—an explicit time-dependent function describing the evolution of all generalized coordinates of a moving system. Such a formulation provides complete information about the system's kinematic behavior.

However, the law of motion is not the sole representation of motion-related information. If the system's differential equations and initial conditions are known, the motion can be described implicitly through the solution of the corresponding Cauchy problem. This approach, while indirect, encapsulates the full dynamics of the system and enables analytical or numerical reconstruction of its trajectory.

In the context of GATS platforms under consideration, each vehicle configuration can be modeled as a nonholonomic system (NHS), consisting of a sequential chain of rigid links connected via rotational joints. These systems are subject to multiple nonholonomic constraints (NHCs), typically exceeding one per configuration. The aggregate of these constraints defines the structure and behavior of the NHS, which governs the platform's maneuverability, especially under reverse motion and in spatially constrained environments.

In analytical mechanics, NHCs are defined as kinematic restrictions expressed by differential equations that, in the general case, cannot be integrated into closed-form functions and must therefore be solved using numerical methods [13]. For a single-link prototype (Fig. 1, link "*K*"), such NHCs may be imposed between any two points of the system, labeled *i* and *j*.

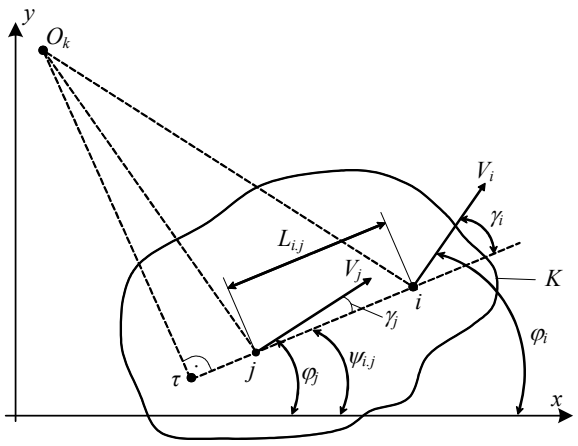


FIGURE 1. Single-link mobile prototype of ground aviation technical support (GATS) equipment.

These constraints define curvilinear motion during planar maneuvering via the relative angles γ_i and γ_j and are formulated as differential equations (each NHCs comprises a pair of equations under the natural choice of motion parameters)

$$\frac{dy_i}{dS_i} - \sin(\psi_{i.j} + \gamma_i) = 0; \quad \frac{dx_i}{dS_j} - \cos(\psi_{i.j} + \gamma_i) = 0; \tag{2}$$

$$\frac{dy_j}{dS_j} - \sin(\psi_{i.j} + \gamma_j) = 0; \quad \frac{dx_i}{dS_i} - \cos(\psi_{i.j} + \gamma_j) = 0. \tag{3}$$

In formulation (2), (3), x_i, y_i, x_j, y_j denote the Cartesian coordinates of points *i* and *j* along their respective trajectories; S_i and S_j are the corresponding arc-length parameters. The symbols γ_i and γ_j represent the relative steering angles of the nonholonomic constraints, measured with respect to the line $L_{i,j}$ connecting the two points. $\psi_{i,j}$ is the absolute orientation angle of the line $L_{i,j}$, and φ_i and φ_j are the absolute steering angles associated with those constraints.

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The angular turning velocity of the GATS prototype is defined by the following equations

$$\frac{d\psi_{i.j}}{dS_i} = \frac{1}{L_{i.j}} \frac{\sin(\gamma_i - \gamma_j)}{\cos\gamma_j}; \quad \frac{d\psi_{i.j}}{dS_j} = \frac{1}{L_{i.j}} \frac{\sin(\gamma_i - \gamma_j)}{\cos\gamma_i}. \tag{4}$$

The control laws governing the steering angles γ_i and γ_j enable the generation of arbitrary planar maneuvers within the nonholonomic framework. However, the effectiveness of this method deteriorates as the steering angles increase, and becomes singular when $\gamma_i, \gamma_j \to \pi/2$, where the system loses controllability due to the degeneracy of the constraint equations. To restore maneuverability under such conditions, it is necessary to redefine the direction of the nonholonomic constraint by selecting an alternative connection line $L_{i.j}$, characterized by a new absolute orientation angle $\psi_{i.j}$. This transition corresponds to the construction of an equivalent nonholonomic system in which the relative steering angles remain sufficiently small. For any auxiliary point 3 located to the right of the initial configuration (denoted as point 3r), the reorientation can be performed using the following expression

$$\gamma_{3r} = arctg\left[\frac{\frac{L_{3.i}}{L_{i.j}} tg\gamma_j - \frac{L_{3.j}}{L_{i.j}} tg\gamma_i}{1 + \frac{L_{3.3r}}{L_{i.j}}(tg\gamma_i - tg\gamma_j)}\right], \tag{5}$$

where $L_{3.i}$, $L_{3.j}$, and $L_{3.3r}$ denote the Euclidean distances between the respective points. This formulation ensures a smooth transition to a well-conditioned constraint geometry, preserving the system's ability to execute complex maneuvers, including reverse motion in spatially constrained environments.

In ground-based mobile GATS prototypes, steering is affected by wheels, each of which imposes a nonholonomic constraint. Although wheels may be located at arbitrary attachment points i, j (or elsewhere), a conventional vehicle typically has four or more wheels. Of these, only two serve as "actuating" wheels, while the remainder are redundant. Under current practice, one of the two actuating wheels is fixed ($\gamma_i \equiv 0$) or both are steered according to the anti-symmetric law $\gamma_j = -\gamma_i$, so that the instantaneous center τ lies midway between points i and j ($\gamma_\tau \equiv 0$). All other steerable wheels are then commanded in accordance with Eq. (1).

The design of advanced steering technologies should, by contrast, allow every wheel to be steerable. Transitioning to an equivalent nonholonomic system makes it possible to derive the required steering laws for any two designated NHCs – real or virtual – thus ensuring the full range of desired maneuvers. In the general case, the vehicle structure comprises multiple rigid links interconnected by joints. Consequently, the overall nonholonomic system assumes a tree topology in which each link is subject to both holonomic and nonholonomic constraints (Fig. 2, 3).

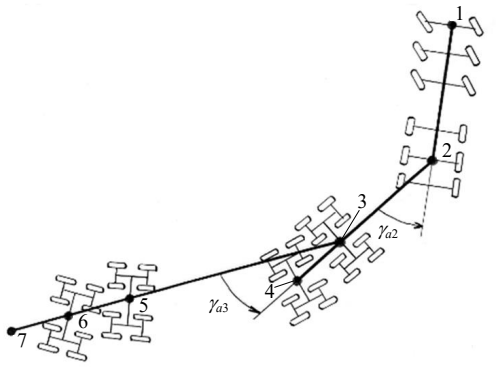


FIGURE 2. Schematic model of the road train chassis illustrating the principal structural nodes and their geometric interconnections.

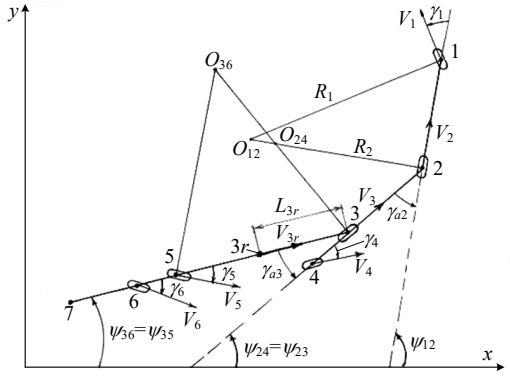


FIGURE 3. Computational scheme for chassis maneuvering control, illustrating the steering logic, constraint configuration, and reference points within the nonholonomic framework.

From the standpoint of maneuvering control in multi-link ground-based mobile systems, it is appropriate to classify structural modules based on their degree of kinematic independence: independent, semi-dependent, and fully dependent (coupled) links.

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Independent links exhibit autonomous motion governed by two actively controlled NHCs, as observed in conventional vehicles or dual-axle trailers. Semi-dependent links – such as single-axle trailers or semi-trailers – are controlled by one NHC in combination with a passive joint. Fully dependent modules (couplers) derive their motion solely from two passive joints that connect them to adjacent links.

The method of equivalent transformation facilitates not only the redefinition of NHCs within individual links but also the structural reclassification of one link type into another. In the following section, this methodology is applied to modular GATS platforms to illustrate its practical applicability.

In the general case, the arc-length coordinates of two points belonging to a sequential chain of links – connected via joints and indexed from β to q – are related through a system of equations that incorporates joint geometry, local steering angles, and nonholonomic constraints. This formulation provides the basis for modeling maneuverability in complex articulated systems

$$\frac{dS_{mp}}{dS_{jp}} = f_{mp\to jp} = \left(f_{mp\to q}\right)\left(f_{q\to\beta}\right)\left(f_{\beta\to jp}\right), \quad f_{mp\to q} = \frac{dS_q}{dS_\beta} = \frac{L_{q.m}\cos\gamma_{q.y} - L_{m.mp}\sin\gamma_{q.y}}{L_{q.m}\cos\gamma_{mp} - L_{m.mp}\sin\gamma_{mp}}, \tag{6}$$

$$f_{q\to\beta} = \frac{dS_q}{dS_\beta} = \frac{\prod_{i=\beta}^{q-1}\cos\left[\gamma_{i.y} \vee (\gamma_{i.x} + \lambda_i)\right]}{\prod_{i=\beta+1}^{q}\cos\left[\gamma_{i.x} \vee (\gamma_{i.y} - \lambda_i)\right]}, \quad f_{\beta\to jp} = \frac{dS_\beta}{dS_{jp}} = \frac{L_{\beta.j}\cos\gamma_{jp} - L_{j.jp}\sin\gamma_{jp}}{L_{\beta.j}\cos\gamma_{\beta.x} - L_{j.jp}\sin\gamma_{\beta.x}}. \tag{7}$$

The preceding equations (6), (7) are supplemented by a set of transition functions – denoted as $f_{mp\to jp}$, $f_{mp\to q}$, $f_{q\to\beta}$, $f_{\beta\to jp}$ – which define the geometric and kinematic relationships between specific reference points indicated by their subscripts. These functions formalize the transmission of arc-length coordinates and angular parameters across a sequence of articulated links. In this framework, point j corresponds to a location positioned forward of point β at a distance $L_{\beta.j}$, while point jp represents a lateral offset from a designated reference point. The relevant angular parameters include: the relative angle at the joint with respect to the preceding (front) link, the relative angle at the joint with respect to the following (rear) link, the articulation angle between two connected links at the joint. These parameters are critical for constructing a generalized maneuvering model of multi-link systems, as they capture both local rotational dynamics and the global propagation of nonholonomic constraints. When applied to a sequential chain of links indexed from β to q, the resulting system of equations establishes a coherent framework for describing motion coordination and constraint coupling throughout the articulated structure.

In many practical scenarios, the natural parametrization of motion enables the complete decoupling of vehicle velocity from the maneuvering control strategy. This invariance with respect to translational speed eliminates a range of methodological concerns, including the validity of solving maneuverability problems and conducting experimental studies under constant-speed conditions, as well as the influence of various velocity profiles on control outcomes. As a result, both the maneuvering control algorithm and the control system itself become velocity-invariant. Moreover, the inverse mapping from arc-length parameter S_i to time t remains admissible and can be performed in a straightforward manner.

For single-link platforms (see Fig. 1), the proposed methodology allows the exclusion of non-steerable wheels – or equivalently, points whose velocity vectors are fixed relative to the link – which typically limit maneuverability and mobility. This approach enables an increase in the system's mobility degree by one in each motion plane, thereby achieving the theoretical maximum for the given configuration. Furthermore, it facilitates the development of advanced maneuvering technologies, including:

– directional control of any two selected points on the platform;
– control of translational motion and rotation of any designated line segment;
– control of the trajectory and local rotation around any chosen point;
– coordinated motion of multiple points and links along unified trajectories.

These capabilities significantly expand the functional range of ground-based autonomous transport systems and provide a foundation for designing high-mobility platforms with enhanced maneuvering precision.

GATS SCALING FRAMEWORK

The proposed framework represents an advancement in the design of kinematic control systems (KCS) for GATS, originally based on a single-axle trailer with non-steerable wheels and conventional hinged coupling to the towing unit. Unlike traditional configurations [14, 15], this approach addresses key control challenges in steering and trajectory stabilization, enabling the development of novel control technologies with the following advantages:

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– stable and controllable motion with any number of trailers positioned in front of the towing vehicle;
– stable and controllable reverse motion with any number of trailers positioned behind the towing vehicle;
– compatibility with single-axle trailers of arbitrary geometric parameters and wheel configurations (including trailers with offset axles), without requiring structural modification;
– full modularity and universality of the KCS design, allowing integration with any production-grade towing vehicle (domestic or foreign) of sufficient power, without retrofitting, and with any number of trailer modules. This ensures applicability across all GATS platforms and supports rapid reconfiguration of vehicle composition in response to changing operational tasks or combat deployment scenarios.

The innovative control technologies developed under this framework are protected by patent [16]. They span four key domains:
– steering control of multi-trailer systems with front-mounted trailers;
– trajectory control of multi-trailer systems with front-mounted trailers;
– steering control during reverse motion with rear-mounted trailers;
– trajectory control during reverse motion with rear-mounted trailers.

The methodology for developing these technologies includes:
– structural analysis of the GATS platform to define the articulated link configuration and wheel formula;
– formulation of the nonholonomic model of the vehicle system;
– construction of an equivalent nonholonomic model incorporating virtual constraints;
– derivation of algebraic expressions for steering angles;
– classification of control regimes (steering, trajectory, directional modes) and specification of operational conditions;
– experimental validation of theoretical solutions and control algorithms, confirming the feasibility and performance of the proposed technologies.

Application of this method has enabled the construction of a fully defined and scalable dimensional series of GATS platforms, supporting modular design and modernization of all aerodrome vehicles. This includes configurations with two, three, or four offset axles (Fig. 4), optimized for operational efficiency and structural unification.

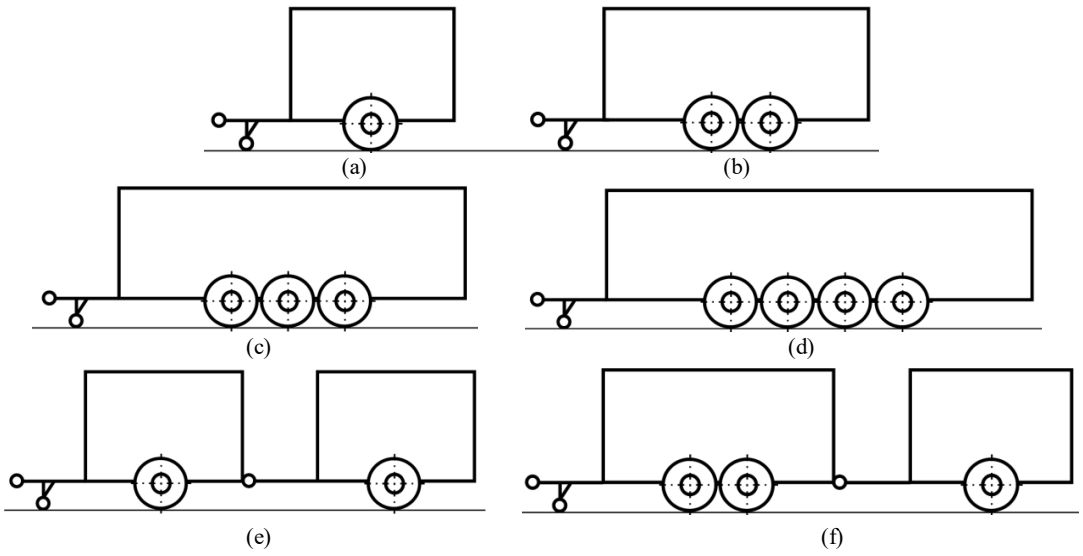


FIGURE 4. Design Variants of Trailer-Based GATS Mobility Systems: (a) conventional single-axle trailer; (b) single-axle trailer with two offset axles; (c) single-axle trailer with three offset axles; (d) single-axle trailer with four offset axles; (e, f) two-link articulated trailer modules.

Accordingly, a fully defined and scalable dimensional series of GATS platforms is proposed, enabling modular design and modernization of all aerodrome transport vehicles currently operated in Ukraine. This series is based on

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the most promising road train configuration, utilizing single-axle trailers with offset axles and incorporating the developed control technologies.

CONCLUSIONS AND DISCUSSION

The presented framework builds upon more than four decades of research in mobile defense and aerodrome support systems. Its foundation lies in the modeling of nonholonomic platforms, where both real and virtual directional constraints—such as wheel geometry, aerodynamic surfaces, and simulated steering elements—are treated as controllable variables. This approach enables a systematic increase in the mobility degree by one in each motion plane, unlocking advanced maneuvering capabilities, including directional control of arbitrary points, coordinated motion of articulated links, and trajectory shaping under spatial constraints.

The proposed control methodology has led to the development of patented technologies for steering and maneuvering of two-link and multi-link modular configurations based on single-axle trailers. These solutions are globally unique and address limitations inherent in conventional systems, particularly in reverse motion and multi-trailer setups. The architecture supports full modularity and universality, allowing integration with any production-grade towing vehicle without structural modification and enabling rapid reconfiguration of convoy composition in response to operational demands.

International validation further supports the effectiveness of this approach. Within the Industry 4.0 and Society 5.0 initiative [17], modular transport systems were studied as part of the digital transformation of airfield infrastructure, emphasizing autonomous control and sensor integration. The deployment of the TLD TractEasy autonomous towing vehicle [18, 19] demonstrated measurable improvements in aircraft servicing time and operational safety. The Horizon Europe ALBATROSS project [20] confirmed the practical benefits of adaptive modularity, showing that reduced equipment density near aircraft can be achieved without compromising functionality.

To ensure reliable implementation, modular GATS systems must comply with international standards regarding lane width, turning radius, and articulation limits. Control algorithms should incorporate steering angle and velocity constraints, while personnel training and simulator-based exercises are essential for safe operation, particularly in reverse mode.

This study introduces a comprehensive methodology for maneuverability control of modular aerodrome support platforms, grounded in nonholonomic modeling and enhanced by virtual steering constraints. The resulting control technologies significantly expand the functional capabilities of mobile systems, offering scalable, reconfigurable, and structurally agnostic solutions for high-density airfield environments.

The proposed framework ensures:

– stable maneuvering with any number of trailers positioned in front of or behind the towing unit;
– compatibility with single-axle trailers of arbitrary geometry and wheel configuration;
– full modularity without the need for vehicle retrofitting;
– adaptability to changing operational and tactical conditions.

Future research should focus on experimental validation under real-world conditions and explore the influence of environmental factors, payload variability, and human interaction on the maneuverability and reliability of modular road train configurations in aerodrome support systems.

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ACKNOWLEDGMENTS

The authors would like to express their gratitude to Ivan Kozhedub Kharkiv National Air Force University.

CONFLICT OF INTERESTS

The authors declare that there is no conflict of interests regarding the publication of this paper.

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