

# *A Review of Aircraft Taxiway Positioning and Navigation Systems*

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**Abstract.** With the continuous expansion of air transportation, airport surface operations are facing increasing pressure in terms of safety and efficiency. During the taxiing phase, aircraft operate in a complex and densely trafficked environment, which is highly susceptible to structural constraints and information uncertainty, leading to risks such as runway incursions and surface conflicts. In this context, improving positioning accuracy and navigation support during the taxiing phase has become a critical means of ensuring safe airport surface operations. This paper presents a comprehensive review of research on aircraft taxiway positioning and navigation systems. From a technical perspective, it focuses on analyzing the characteristics and limitations of satellite-based positioning methods, ground surveillance and sensor-based positioning techniques, vision-based and intelligent perception approaches, and multi-source information fusion positioning technologies in airport surface scenarios. On this basis, recent advances in aircraft taxiway path planning and navigation methods are further reviewed, including multi-objective path optimization, taxi navigation under dynamic operating environments, and navigation decision-support techniques. This review provides a systematic understanding of the main research directions and development trends in aircraft taxiway positioning and navigation systems, and serves as a reference for future research and engineering applications.

**Keywords:** Aircraft taxiway, Positioning and navigation, Airport surface operations, Multi-source information fusion, Taxi path planning

## **1. Introduction**

Airport surface operations represent one of the most risk-intensive stages in the air transportationsystem, with the aircraft taxiing phase being particularly critical. According to statistics fromtheFederal Aviation Administration, a considerable number of runway incursion events arestillreported annually within the U.S. National Airspace System as of 2024, indicating that safetychallenges in airport surface operations remain significant [1]. Under high-density operationalconditions, aircraft taxiing increasingly relies on precise positioning and reliable navigationsupport,and the performance of related technologies has a direct impact on both safety and operationalefficiency.

Research on aircraft taxiway operation support has primarily focused on human–machine interaction design, positioning and surveillance technologies, and taxi path planning. In the area of human–machine interaction, electronic moving maps and taxi route guidance have been widely adopted to enhance pilots’ situational awareness, with simulation-based or experimental evaluations used to assess the effects of different information presentation modes on operational performance [2]. In terms of positioning and surveillance, advances in computer vision and deep learning have led to the application of vision-based approaches to airport surface monitoring, enabling automatic detection and tracking of aircraft and key surface targets [3]. Meanwhile, some studies model the taxiing process as a multi-objective optimization problem, performing path planning by jointly considering taxi time, safety constraints, and operational efficiency [4].

Against this background, this paper focuses on aircraft taxiway positioning and navigation systems and provides a systematic review of related technologies and methods, with emphasis on positioning techniques, taxi navigation approaches, and decision-support research, offering an integrated reference for future studies.

## **2. Research status of aircraft taxiway positioning and navigation systems**

### **2.1. Aircraft taxiway positioning technologies**

#### **2.1.1. Satellite-based positioning technologies**

Satellite-based positioning technologies constitute the most widely used foundational approach within aircraft taxiway positioning systems. During the taxiing phase, GNSS offers advantages such as technological maturity, wide coverage, and good continuity, providing stable position updates for navigation systems. However, compared with airborne environments, airport surface environments are characterized by dense buildings and facilities, where multipath effects are pronounced and can significantly degrade positioning accuracy and stability.

To address this issue, existing studies have analyzed the error characteristics of GNSS in airport surface scenarios, identifying multipath effects as one of the primary sources of positioning error during taxiing, with distribution patterns that differ markedly from those in open environments. By modeling airport surface environments, the variation characteristics of multipath errors can be more accurately described, providing a basis for performance evaluation and error mitigation in positioning systems. Related studies indicate that relying solely on GNSS is insufficient to meet the high-accuracy and high-reliability requirements of the taxiing phase [5].

In summary, satellite navigation plays an indispensable foundational role in taxiway positioning; however, its accuracy remains constrained in complex surface environments. Enhancing ground positioning reliability while maintaining the continuity advantages of GNSS remains a key research focus.

#### **2.1.2. Ground surveillance and sensor-based positioning technologies**

In addition to satellite-based positioning methods, a variety of ground surveillance and sensor-based technologies have been developed and applied in airport surface operations. These methods do not directly participate in position computation but instead continuously monitor aircraft positions and motion states through ground-based systems, providing important supplementary information for taxiway positioning and navigation in complex airport environments.

Automatic Dependent Surveillance–Broadcast (ADS-B) is a core component of modern airport surface surveillance systems. Based on position solutions generated by onboard navigation systems, aircraft periodically broadcast their position and motion parameters, enabling ground receivers to obtain real-time aircraft state information. Compared with traditional radar-based surveillance, ADS-B offers higher update rates and wider coverage and has therefore been widely adopted in airport surface monitoring. However, since ADS-B fundamentally relies on onboard navigation solutions, its positioning accuracy and reliability are inevitably influenced by GNSS performance and signal conditions.

In practical engineering systems, no single surveillance method can fully satisfy the requirements for continuity and reliability in airport surface operations. Consequently, multiple surveillance techniques are typically employed in a coordinated manner. The Airport Surface Surveillance Capability system proposed by the Federal Aviation Administration integrates ADS-B, radar, and other surveillance sources to achieve unified monitoring and management of surface targets, significantly enhancing surface situational awareness in operational practice [6].

Furthermore, historical and real-time trajectory data generated through ADS-B provide valuable data resources for airport surface operation analysis and positioning research. Publicly available studies have utilized terminal-area trajectory datasets to analyze aircraft operational behavior in airports and surrounding areas, including position variation characteristics during taxiing [7]. Such data support not only operational assessment and efficiency analysis but also the validation and optimization of taxiway positioning and navigation systems.

Overall, ground surveillance and sensor-based positioning technologies exhibit high engineering maturity but limited standalone positioning capability. They are better suited as complementary components to satellite navigation, operating in coordination with other positioning methods.

### **2.1.3. Vision-based and intelligent perception positioning methods**

Vision-based and intelligent perception positioning methods have increasingly been introduced into airport surface operation research, providing new technical pathways for taxiway positioning. These approaches acquire surface images or video data through camera systems and utilize object detection and tracking algorithms to perceive aircraft and relevant environmental elements.

Existing studies have constructed airport surface visual perception frameworks based on deep learning techniques, enabling the recognition and tracking of runways, taxiways, and aircraft targets [3]. To address the large spatial scale of airport surfaces and the wide range of target distances, some research has incorporated multi-scale feature extraction and fusion mechanisms to improve recognition performance under varying viewing conditions [8].

Despite their advantages in environmental understanding, vision-based methods still face limitations in taxiway positioning applications. Visual perception is sensitive to lighting conditions, weather, and occlusions, and it is difficult to provide stable absolute positioning information independently. Consequently, current studies mainly employ vision-based approaches to enhance airport surface situational awareness rather than as standalone positioning solutions.

### **2.1.4. Multi-source fusion positioning technologies**

During airport surface taxiing, the stability of any single positioning or surveillance method is difficult to maintain over extended periods, making multi-source fusion positioning an important direction for improving reliability. This approach integrates observations from different sensors and surveillance systems, partially compensating for their respective systematic errors. In airport surface

applications, commonly fused data sources include enhanced GNSS positioning results, ADS-B broadcasts, and multilateration-based position estimates. These data sources differ in update rates, error characteristics, and coverage, providing complementary conditions for fusion algorithms.

Several studies have systematically explored multi-source fusion positioning from an algorithmic perspective. One approach employs an interacting multiple model filter to incorporate data from various positioning and surveillance sensors into a unified state estimation framework, dynamically adjusting model weights to accommodate changes in sensor performance. Experimental results demonstrate that, through multi-source collaboration, fusion-based positioning outperforms single-sensor outputs in both accuracy and continuity, offering a mature algorithmic reference for aviation positioning applications [9].

In airport surface surveillance scenarios, discrepancies among data sources introduce additional challenges for fusion processing, including differences in time synchronization accuracy, noise characteristics, and data completeness. To address these issues, some studies have introduced attention-based fusion strategies that learn the relative importance of different data sources under varying conditions, enabling adaptive adjustment of fusion weights. Such methods have been shown to alleviate certain limitations of traditional fixed-weight fusion approaches when processing multi-source surface surveillance data [10].

In summary, multi-source fusion provides a feasible engineering pathway for improving airport surface positioning. However, trade-offs among real-time performance, system complexity, and data quality dependence remain, making fusion techniques more suitable as enhancement mechanisms used in coordination with other positioning technologies.

## 2.2. Aircraft taxiway path planning and navigation methods

### 2.2.1. Taxiway path planning and optimization methods

Aircraft taxiway path planning is considerably more complex than conventional shortest-path problems, as it must simultaneously satisfy safety separation requirements, operational priorities, and conflict avoidance constraints.

In most studies, airport taxiway systems are first abstracted as network structures composed of nodes and directed edges, where nodes correspond to taxiway intersections, parking stands, or runway entry points, and edges represent traversable taxiway segments. Based on this abstraction, path planning can be formulated as the search for feasible paths under given constraints. Some studies have proposed spatial-temporal bilevel optimization models that introduce time dimensions into path planning, enabling coordinated optimization of route selection and taxi schedules [11]. This approach reflects the reality that taxi conflicts are often closely related to temporal arrangements.

As research has progressed, single-objective optimization has been deemed insufficient for meeting practical airport operational requirements. A taxi route with minimum travel time does not necessarily correspond to minimum fuel consumption and may introduce conflict risks under high-density operations. Consequently, multi-objective path planning methods have attracted increasing attention. Relevant studies construct optimization objectives from perspectives such as time efficiency, fuel consumption, and environmental impact, employing multi-objective optimization algorithms to identify trade-off solutions among competing goals [4]. While these methods offer richer decision alternatives, they also impose higher demands on computational efficiency and parameter configuration.

In application-oriented research, path planning often needs to account for the coordinated operation of multiple aircraft. Some studies adopt multi-agent approaches, modeling each aircraft as an independent decision-making entity and introducing time-window mechanisms to avoid taxi conflicts [12]. This strategy reduces the computational burden associated with centralized planning and aligns more closely with distributed decision-making characteristics in airport surface operations. However, its effectiveness depends heavily on accurate conflict prediction and temporal coordination modeling.

Overall, aircraft taxiway path planning has evolved from static shortest-path searches toward comprehensive optimization that considers time, energy consumption, and multi-aircraft coordination. Under high-density operations and dynamic disturbances, planned routes still require continuous adjustment, motivating further research into dynamic replanning and real-time optimization mechanisms.

### **2.2.2. Taxi navigation methods for dynamic operating environments**

In real-world airport operations, aircraft taxiing rarely follows preplanned routes exactly. Factors such as flight delays, temporary taxiway closures, waiting for preceding aircraft, and changes in operational priorities can gradually invalidate original planning assumptions. Under such conditions, static one-time path planning is insufficient, and taxi navigation systems must be capable of adjusting in response to real-time operational states.

Some studies propose dynamic control methods for airport surface operations by incorporating adaptive traffic situation assessment mechanisms that continuously adjust taxi processes [13]. Within such frameworks, planned routes are iteratively modified as surface traffic conditions evolve, improving overall coordination. Data-driven conflict prioritization mechanisms further enable navigation decisions to better reflect actual operational needs by categorizing and handling potential conflicts according to their urgency [13].

However, dynamic navigation approaches place higher demands on computational efficiency and system responsiveness. Excessively frequent adjustments may increase execution complexity, necessitating careful trade-offs between adaptability and operational stability in practical applications.

### **2.2.3. Taxi navigation decision support and system implementation methods**

In actual airport operations, even well-designed path plans may be disrupted by speed variations, holding instructions, or temporary dispatch adjustments, causing deviations during execution. Sole reliance on position displays or path planning is often insufficient to support safety and efficiency under high-density operations. Accordingly, some studies shift their focus from positional data to control command modeling, recognizing that taxi clearances, holding instructions, and adjustment commands issued by controllers implicitly convey future operational states.

Based on this perspective, certain studies analyze historical operational data to summarize execution patterns associated with different control commands, thereby predicting subsequent taxiing behavior and assessing potential conflict risks [14]. This approach does not depend on absolute positioning accuracy but instead emphasizes inference at the operational logic level, providing auxiliary decision support and enabling early identification of possible taxi conflicts. By integrating control commands with real-time situational data, systems can dynamically generate risk alerts and enhance controllers' situational awareness and judgment in complex traffic environments.

In engineering practice, such methods are typically deployed as supplementary functions within existing taxi navigation systems rather than as standalone solutions. Their effectiveness relies on foundational information from positioning, surveillance, and path planning modules and requires careful balancing between real-time performance and system complexity. Overall, control-command-based decision support introduces additional safety redundancy into airport surface operations and provides a foundation for intelligent decision-making and conflict management in future multi-source fusion navigation systems.

### 3. Conclusion

This paper presents a systematic review of research on aircraft taxiway positioning and navigation systems. From the perspective of practical airport surface operation requirements, recent advances in taxiway positioning technologies, taxi path planning and navigation methods, and taxi navigation decision support have been comprehensively analyzed to capture the overall development landscape and technical characteristics of this field.

In terms of positioning technologies, this review summarizes satellite-based positioning, ground surveillance and sensor-based methods, vision-based perception approaches, and multi-source fusion techniques. Existing studies indicate that each single positioning method exhibits inherent limitations in complex airport surface environments. GNSS offers good continuity and engineering maturity but is vulnerable to multipath effects; ground surveillance systems provide high reliability yet limited independent positioning capability; vision-based and intelligent perception methods enhance environmental understanding but cannot independently deliver stable absolute positioning. Consequently, multi-source fusion has emerged as an important direction for improving taxiway positioning reliability, although challenges remain in real-time performance, system complexity, and data quality dependence.

Regarding taxi path planning and navigation methods, research has evolved from static shortest-path formulations toward complex decision problems incorporating time constraints, multi-objective optimization, and multi-aircraft coordination. To address operational uncertainty, dynamic control and real-time adjustment mechanisms have been introduced, enabling taxi navigation systems to better adapt to changing traffic conditions. Furthermore, decision-support methods based on control commands and operational data provide new perspectives for managing taxi safety, reflecting a shift from pure path planning toward integrated operational assistance. Overall, while notable progress has been achieved across multiple technical directions, limitations remain at the system integration level. Many studies focus on individual technologies or localized problems, with relatively limited attention to the coordinated design of positioning, navigation, and decision-support components. Future research may further strengthen system-level investigations within multi-source information fusion frameworks, validate methods using real operational data, and balance safety, system complexity, and deployability to support the intelligent and safe evolution of airport surface operations.

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