Defining Requirements for Safe, Scalable, and Seamless Surface Navigation for UAS: Challenges and Perspectives

Sabrina Ugazio[1]
Ohio University, Athens, OH, 45702, USA

Mathieu Joerger[2]
Virginia Polytechnic Institute and State University, Blacksburg, VA, 24061, USA

Daniel J Larimer[3], Kana Nagai[4]
Illinois Institute of Technology, Chicago, IL, 60616, USA

Jay Wilhelm[5], Brian C. Peters[6], Ryan McKnight[7]
Ohio University, Athens, OH, 45702, USA

The main obstacle to autonomous navigation operations for large UAS in civil airspace is the lack of safe and reliable automatic taxiing, takeoff, and landing. The SurfNav4UAS project aims at addressing the challenges of automatic taxiing, with a specific focus on developing safe, scalable, and seamless navigation methods that meet the unique accuracy, integrity, and continuity requirements of automatic surface operations. This work outlines the methodology for defining navigation requirements.

I. Introduction

The integration of large Uncrewed Aircraft Systems (UAS) into the National Airspace System (NAS) requires navigation capabilities that support safe, scalable, and certifiable autonomous surface operations. While significant progress has been made in other enabling technologies, surface navigation remains a major unresolved barrier, as identified by RTCA SC-228 [1]. The majority of the documentation developed so far related to navigation requirements for surface operations at airports is related to aircraft with pilot on-board, where the pilot relies on visual checks to validate and mitigate errors of the navigation system. Therefore, requirements are typically tied to visibility conditions, with more stringent performance needed under reduced visibility. FAA AC 120-28D [2] provides guidance

[1] Assistant Professor, School of EECS, Ohio University
[2] Associate Professor, Kevin T. Crofton Department of Aerospace and Ocean Engineering, AIAA Senior Member
[3] Research Engineer, CARNATIONS Lab
[4] Senior Research Associate, Department of Mechanical and Aerospace Engineering
[5] Associate Professor, Department of Mechanical Engineering, AIAA Associate Fellow
[7] PhD Candidate, School of EECS
[8] Postdoctoral Research Scholar, Avionics Engineering Center

for integrity and continuity expectations during low-visibility landing and rollout for piloted aircraft, which can be adapted to identify requirements for autonomous systems.

RTCA DO-247 [3] addresses airport surface operations with an emphasis on the navigation segment and, in particular, on Global Navigation Satellite System (GNSS) performance. The assessment of GNSS performance for surface operations demonstrates both the potential and limitations of satellite-based navigation for airport environments. DO-247 proposes analytical methodologies for evaluating performance for surface movement and highlights the need for extensive in-field validation.

In [4,5,6,7], Schuster et al consider performance requirements for gate-to-gate operations, including airport surface operations, based on a GNSS, multi-system and multi-frequency, navigation solution. In [5], concepts of operations (CONOPS) are considered for different airports and aircraft, and the total system error (TSE) and the navigation system error (NSE) are derived, under zero visibility.

More recent analyses reaffirm the need for integrity-assured surface navigation systems, augmenting GNSS with other systems. For example, Song et al. (2024) [8] revisited manned surface-navigation performance using updated models for ground-based augmentation and inertial coupling, reaffirming the need for integrity-assured surface navigation and the related challenges.

The documents cited above provide a valid starting point to derive the navigation requirements for UAS. However, their scope was restricted to piloted aircraft, their content was tied to visibility categories, and they assumed that the pilot provides a significant integrity buffer: the UAS navigation requirements need to be adjusted properly. As a result, DO-247 requirements cannot be directly applied to autonomous UAS. Unlike piloted aircraft, autonomous UAS rely entirely on their onboard navigation system to safely execute the operations of taxiing, runway rollout, and pre-takeoff.

Documents such as the ICAO's [9] and more recently [10], as well as the EUROCAE's [11] aim to define performance requirements to support the development of solutions to enhance safety and or capacity-related issues. Other documents, such as [12], build on these requirements to provide specifications for the implementation of an Advanced Surface Movement Guidance and Control System (A-SMGCS) at an airport (or more generally, at an aerodrome).

All these existing standards assume the presence of a pilot and rely on visibility categories that are generally irrelevant for UAS. Thus, the literature shows a persistent gap: there is no existing set of requirements defining the minimum performance that a navigation system must achieve to support autonomous UAS surface operations. These requirements must be independent of the specific sensors or augmentation methods used. Emerging operational concepts for autonomous UAS require navigation systems with certifiable performance levels suitable for integration into the NAS.

This paper discusses a methodology for deriving surface-navigation requirements for UAS. It is written under the NASA University Leadership Initiative (ULI) project SurfNav4UAS, which specifically focuses on navigation solutions for autonomous surface operations. This paper presents the procedure to derive requirements applicable to various navigation architectures, including GNSS and Inertial Navigation System (INS) augmented with other sensors (e.g., computer vision [CV]) and GNSS/INS with ground-based augmentation.

II. Background

The SurfNav4UAS project

The challenge discussed in this paper is related to the on-going work within the "Safe, Scalable, and Seamless Surface Navigation for UAS" project (SurfNav4UAS) project, funded through the NASA University Leadership Initiative (ULI). The project specifically targets the surface-navigation portion of the SC-228-identified gap, encompassing takeoff roll, landing rollout, and taxiing. While the approach and landing phases have seen considerable technological advancement through systems such as ILS CAT IIIb and the under-certification Ground-Based Augmentation System (GBAS) GAST D that enable fully automated landing to touchdown, surface operations were excluded from GBAS certification due to their extremely demanding performance requirements introduced by narrow taxiways. Surface navigation introduces additional challenges which are less prevalent in airborne phases, primarily driven by the more multipath-rich environment of the airport surface. The proximity of taxiing aircraft to buildings, vehicles, and other aircraft increases the likelihood of signal blockage and multipath interference. Furthermore, it is envisioned that UAS may commonly employ vision-based navigation systems which can serve to significantly enhance the performance and robustness of surface navigation while introducing their own suite of challenges in terms of requirement definition and evaluation of integrity. Four technical challenges (TCs) have been defined which the SurfNav4UAS project aims to address. These technical challenges are summarized in Table 1. The present work focuses on TC-1, which serves as a necessary first step to guide technology development.

Table 1: SurfNav4UAS project technical challenges.

Technical Challenge (TC)	Description
TC-1: Navigation performance requirements for UAS automatic surface operations	Develop minimum navigation performance requirements for large fixed-wing UAS automatic surface operations.
TC-2: Development of CV-based augmentation for UAS surface operations	Develop and demonstrate an integrated GNSS / INS / CV architecture to increase availability, accuracy, integrity, and continuity beyond GNSS alone to meet the derived performance requirements.
TC-3: Development of ground-based GNSS augmentation for UAS surface operations	Develop and demonstrate an integrated differential GNSS / INS architecture to increase availability, accuracy, integrity, and continuity beyond GNSS alone to meet the derived performance requirements.
TC-4: Transition solution into a TRL 6 product	Transition the analysis, algorithms, and prototype hardware to industry partners for development into a standalone product with a low deployment cost.

Motivations

One of the challenges of autonomous UAS surface operations is to navigate the airport environment. All the operations occur within the airport movement area, an environment characterized by narrow containment margins and frequent intersections. Another major factor to be taken into account is the mixed traffic involving crewed aircraft and ground vehicles; however, the scope of this work is focused on the navigation solution, and an environment without obstacles to motion is assumed. The detection and avoidance (DAA) problem will need to be addressed separately.

Autonomous UAS surface operations introduce a fundamentally different set of navigation requirements from those traditionally considered for piloted aircraft. In conventional operations, highly trained pilots maintain situational awareness using visual cues; in [8], following [3], it is assumed that the pilot succeeds in mitigating the continuity risk consistently but fails once in 10,000 cases across all sub-phases, and fails to mitigate the integrity risk in 1 out of 20 cases in taxi lane and gate areas, and in 1 out of 10 cases during the remaining phases [8]. When the pilot is removed from the loop, the navigation subsystem becomes the sole provider of position and velocity information, and therefore must satisfy more stringent requirements for accuracy, continuity, availability, and integrity across all phases.

Prior studies and standards offer valuable insights but do not deliver a complete framework suitable for autonomous UAS. RTCA DO-247 provides methods for deriving requirements for airport surfaces; however, these thresholds are tied to visibility conditions, which do not directly apply to UAS, and assume pilot involvement in detecting navigation failures. In piloted systems, navigation requirements can be looser because the pilot can compensate for part of the errors: visibility conditions drive the required performance. With UAS, the autonomous system requires consistent navigation performance independent of visibility conditions. Further considerations regarding visibility would be necessary only if the navigation system depends on visual sensors. However, in this paper, the CONOPS and requirements are discussed independently of the system utilized to reach those requirements.

Moreover, DO-247 focuses on GNSS (GNSS/INS plus augmentation) performance without accounting for modern sensor-fusion architectures. Thus, while DO-247 helps motivate the required order of magnitude for performance levels and sets a baseline for the approach to derive requirements, its assumptions limit direct applicability to autonomous operations.

Recent research highlights the ongoing challenge of meeting surface-navigation performance with architectures focused on GNSS. Song et al. (2024), still focused on systems with a pilot, revisited the feasibility of GNSS/INS systems supported by ground-based augmentation and relative receiver autonomous integrity monitoring (RRAIM), concluding that achieving the necessary protection-level and integrity margins on the airport surface remains challenging [8]. Importantly, their work reinforces the idea that requirements must be established independently of any one sensor technology. Before assessing whether an architecture such as GNSS/INS with computer vision or GNSS/INS with GAST-D can meet operational needs, the requirements themselves must be clearly defined based on safety objectives and operational constraints.

Operational frameworks such as the ICAO Advanced Surface Movement Guidance and Control System (A-SMGCS) Manual provide a functional decomposition of airport surface operations - surveillance, routing, guidance, and control - within which navigation is a supporting function of the guidance and control operations [3]. While A-SMGCS does not explicitly specify navigation performance requirements, it provides the operational context necessary to infer them. The manual also emphasizes the complexity of airport surface movement, including interactions with other aircraft and vehicles – which is not considered in this work, as mentioned above.

III. Concepts of Operation

The SurfNav4UAS project focuses on these issues under the assumption that no obstacles will be present on the airport surface. The challenge of autonomous UAS surface operations is intrinsic to environmental characteristics, detailed in [13]. All operations occur within the airport movement area, an environment characterized by narrow containment margins, and frequent intersections. Another major factor to be taken into account is the mixed traffic involving crewed aircraft and ground vehicles; however, the scope of this work is focused on the navigation solution, assuming an environment clear of obstacles to motion. The UAS must navigate this environment without a pilot. This differs fundamentally from piloted operations, where pilot visual cues and judgment provide a major safety buffer. As a result, the performance of the navigation subsystem must remain consistently reliable across all airport areas and under all visibility and environmental conditions.

The ICAO A-SMGCS manual [9,10] points out that the navigation solution is part of a more complex system, supporting a capability that enables guidance and control to follow designated taxi routes and comply with operational constraints. In this setting, the navigation system provides the position, velocity, and timing (PVT) information together with integrity indications, that the autonomous system will use to execute the planned route maintaining lateral containment, regulating speed and execute maneuvers, including stop operations at the pre-determined points. Because navigation is coupled to the vehicle’s motion control, its performance must be both accurate and timely to prevent undesirable operations.

A typical surface operation begins either with taxi from the gate/hangar and pre-takeoff alignment, or with runway rollout after landing and taxi to the gate/hangar. Each phase may involve different requirements on the navigation system. Neglecting the DAA problem, in a clear-of-obstacles environment, the runway centerline must be tracked and proper hold points must be respected. The requirements and margins become stricter depending on the taxiway size as well as the aircraft size. Similarly, the requirements tighten during pre-takeoff alignment. Other critical operations involve taxi along curved portions of the route, where tighter geometry leads to smaller error margins. The risk associated with each phase also determines the required integrity level. For example, the risk of runway incursion is higher than that of exiting the taxilane on the side.

RTCA is currently working on Automatic Surface Operations Operational Services and Environment Definition (OSED), as well as on the Minimum Aviation Systems Performance Standards (MASPS) for Surface Hazard Avoidance for Automatic Taxi and Navigation MASPS for Automatic Taxi.

Autonomy-specific hazards can be identified, such as incorrect runway entry and failure to stop at hold positions that must be considered in the definition of navigation performance thresholds. In piloted operations, many of these hazards are mitigated through visual monitoring and pilot intervention, assumptions embedded in earlier standards such as DO-247. Autonomous UAS cannot rely on such supervision, and therefore the navigation system must provide a higher level of performance.

Several prior studies underscore the sensitivity of surface operations to navigation performance. Based on the prior documents, in particular [3], Schuster and Ochieng [5,7] showed how the narrow spatial margins of taxiway operations impose stringent accuracy requirements, and Amielh et al. [14] showed that GNSS-based systems may face limitations in the airport surface environment, followed up by more recent analyses, such as Song et al [8]. The recent study in [15] further strengthens and quantifies this operational scenario.

The concept of operations considers detailed information such as taxilane width, aircraft wingspan, and aircraft speed, since these operational characteristics drive the required navigation integrity for automatic surface operations. These integrity requirements also account for the initialization process, referring to the period required for the navigation filter to converge to a reliable state estimate and covariance. Based on these definitions, Larimer et al. derive the corresponding navigation integrity requirements and the required initialization behavior, such as the minimum time the system remains at the gate or hangar before routing begins [15].

Requirements definition

The definition of navigation requirements for autonomous UAS surface operations must be derived from operational constraints, hazard severity, and containment geometry, rather than from the limitations of any particular sensing technology. Standards such as RTCA DO-247, the ICAO A-SMGCS Manual, FAA AC 120-28D provide important foundations for performance modeling, but they assume the presence of a pilot and visibility-dependent categories, and therefore are not directly applicable to autonomous systems. Earlier investigations by Schuster and Ochieng [7] conducted under zero-visibility conditions provide a good starting point for further analysis, as they apply the integrity requirements used for CAT III landing. Taxiway and taxilane design margins directly translate into allowable Total System Error (TSE). In the work presented in [7], Path Definition Error (PDE), Flight Technical Error (FTE), and Navigation System Error (NSE) are derived using TSE formulations consistent with CAT III requirements. Given this context, requirements must first focus on the automatic taxi system and then on the requirements needed for the navigation subsystem, while remaining architecture-agnostic.

Automatic Taxi System Requirements

The automatic taxi system integrates navigation and other functions to follow assigned routes properly. In Schuster and Ochieng [7], the TSE represents the overall allowable lateral error that keeps an aircraft within safe limits during surface movement. TSE is driven by airport design constraints, specifically the travel surface clearance (TSC), and for taxiways in gate areas the wingtip-to-(nearest-)object (WTO) distance. In [11] the assumption is to be in zero-visibility conditions and that surface-movement safety must be at least as stringent as CAT III landings, which limit the probability of exceeding lateral boundaries to 10^{-6} and the 95% TSE values are computed for each airport category and travel surface. For large commercial airports (Categories D–F), the resulting TSE requirements range from 1.8–2.0 m for taxiways, 1.1–1.3 m for taxilanes, and 0.8–0.9 m for gate areas. These values represent the total allowable error budget that must encompass navigation uncertainty, steering inaccuracies and all the other errors including mapping errors.

Navigation Subsystem Requirements

The navigation subsystem a PVT solution with integrity, capable of supporting autonomous taxi under the constraints described above. To isolate the contribution of the navigation subsystem, the TSE needs to be decomposed into independent error components: the Navigation System Error (NSE), Path-Steering Error (PSE), and Aeronautical Data Quality (ADQ) [7]. This relationship is expressed as $\sigma_{\mathrm{TSE}}^2 = \sigma_{\mathrm{NSE}}^2 + \sigma_{\mathrm{PSE}}^2 + \sigma_{\mathrm{ADQ}}^2$. Given known or assumed performance for ADQ (typically 0.5 m for centrelines and intersections) and empirically derived PSE values, the allowable NSE is obtained by subtracting these contributions from the total error budget implied by the TSE figures. The resulting NSE requirements quantify the performance that the onboard navigation system must satisfy to enable safe operation in zero-visibility conditions. For major airports (Categories D–F), and assuming current ADQ and typical PSE values, the derived (95%) NSE requirements in [7] are approximately 1.0 m for taxiways, 0.6 m for taxilanes and gate areas. The NSE values ultimately define the performance targets that any candidate navigation solution must meet to enable safe autonomous surface operations.

The performance requirements in [7] provide a baseline for application-specific analyses that incorporate UAS-specific CONOPS. Further research is needed to analyze practical UAS-based scenarios. For example, Larimer et al. compute NSE requirements for taxilanes and taxiways using the probabilistic framework in [15]. Assuming a zero-mean Gaussian NSE, the resulting per-test NSE standard deviation allocations are 0.11 m for taxilanes and 0.16 m for taxiways for Aircraft Design Group I (ADG I). Automatic surface operations within these requirements are shown to be feasible with a carrier phase differential GNSS-based navigation system [15]. At the same time, further work may help refine requirements for airport-map performance as well, including both accuracy and integrity aspects.

IV. Conclusions

The goal of this paper was to outline the elements that must be considered when defining navigation requirements for autonomous UAS surface operations. Existing standards and prior studies were developed for manned aircraft and often rely on assumptions, such as visibility conditions and pilot-driven error mitigation, which do not carry over to autonomous systems. By revisiting these sources with UAS-specific considerations in mind, we identified a baseline set of performance requirements and the parameters that must be accounted for in further analyses to refine thresholds for UAS operations, as some of the current baseline values may be conservative and difficult to satisfy. At the same time, future needs may lead to additional recommendations to improve airdrome mapping performance, enhancing both accuracy and integrity. While work is ongoing to define requirements for surface operations, the SurfNav4UAS project will provide real data and validation of these requirements, supporting their refinement and helping advance navigation solutions suitable for autonomous UAS operating in the NAS.

Acknowledgments

This work was carried out in the framework of the SurfNav4UAS project, supported by the NASA University Leadership Initiative (ULI).

The authors would like to acknowledge Andrew Videmsek from Reliable Robotics Corporation for his sustained support and regular technical guidance, which played an important role in this work. The authors also acknowledge Tim Murphy from The Boeing Company for his insightful discussions and constructive contributions during the project.

References

[1] RTCA SC-228, SC-228, "Minimum Operational Performance Standards for UAS," RTCA, Washington, D.C.

[2] Federal Aviation Administration, "AC 120-28D: Criteria for Approval of Category III Weather Minima for Takeoff, Landing, and Rollout," 1999

[3] RTCA (1999), DO-247, "The Role of the GNSS in Supporting Airport Surface Operations," https://my.rtca.org/productdetails?id=a1B36000001IcjpEAC

[4] Schuster, W., Ochieng, W., "Gate-to-Gate with Modernized GPS, GALILEO and GBAS - Harmonization of Precision Approach Performance Requirements," Proceedings of the 19th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS 2006), Fort Worth, TX, September 2006, pp. 437-448.

[5] Schuster, W., Bai, J., Feng, S., and Ochieng, W., "Airport Surface Movement - Performance Requirements, Architecture Considerations & Integrity Algorithms," Proceedings of the 20th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS 2007), Fort Worth, TX, September 2007, pp. 2950-2961.
[6] Schuster, W., Bai, J., Ochieng, W., Schachtebeck, P. M., and Steen, M., "High Performance Navigation Algorithms for Aviation - Results of Approach and Airport Surface Movement Tests," Proceedings of the 21st International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS 2008), Savannah, GA, September 2008, pp. 2901-2908.
[7] Schuster, W. and Ochieng, W., "Airport Surface Movement – Critical Analysis of Navigation System Performance Requirements. Journal of Navigation," Vol. 64, No. 2, 2011, pp. 281-294. https://doi.org/10.1017/S0373463310000500
[8] Song, J., and Milner, C., "Feasibility Study of GBAS/INS and RRAIM for Airport Surface Movement Under Low-Visibility Conditions," NAVIGATION, Vol. 71, No. 4, 2024, https://doi.org/10.33012/navi.673
[9] International Civil Aviation Organization, "Advanced Surface Movement Guidance and Control Systems (A-SMGCS) Manual," Doc 9830, 1st ed., Montréal, 2004.
[10] International Civil Aviation Organization, "Advanced Surface Movement Guidance and Control System (A-SMGCS) Manual," Doc 9830, 2nd ed., Montréal, 2022.
[11] European Organization for Civil Aviation Equipment, ED-87E, "MASPS for A-SMGCS including Airport Safety Support Service Routing Service and Guidance Service," 2022
[12] EUROCONTROL-SPEC-171 Version 2.0 (22/04/2020): "EUROCONTROL Specification for Advanced-Surface Movement Guidance and Control System (A-SMGCS)
[13] International Civil Aviation Organization "Aerodrome Design and Operations," Annex 14, Volume 1, 5th Edition, Montreal, 2009
[14] Amielh, C., Chabory, A,, Macabiau, C., and Azoulai, L., "GNSS Multipath Error Model for Aircraft Surface Navigation Based on Canonical Scenarios for Class F Airports," Proceedings of the 32nd International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2019), Miami, Florida, September 2019, pp. 1418-1437. https://doi.org/10.33012/2019.16907
[15] Larimer, D. J., Khanafseh, S., Nagai, K., Pervan, B., "High-Integrity Surface Navigation for Unmanned Aircraft: A Multi-Frequency GNSS Approach," Proceedings of the 38th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2025), Baltimore, Maryland, September 2025, pp. 311-332. https://doi.org/10.33012/2025.20305