Enabling Smart Urban Airspaces through Distributed Sensing Technologies

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Distributed sensing systems offer potential for enhancing safety and efficiency in urban airspaces and low-altitude metropolitan flight corridors. These systems leverage sensor networks to provide real-time airspace monitoring, situational awareness, and data for decision-making. This paper examines application of distributed sensing and smart airspace concepts to enable advanced urban flight, focusing on critical need applications such as airspace monitoring, corridor surveillance, precision navigation, and hazard avoidance. Benefits such as improved monitoring and increased situational awareness of activity within the urban airspace are considered alongside challenges in system design and implementation. This paper summarizes an ongoing effort to study the feasibility and effectiveness of distributed sensing systems for enabling urban airspace operations. Current research and design considerations are summarized, and a proposed roadmap for future work is presented.

I. Introduction

With the rapid growth of urbanization and increased utilization of airspace, the need for effective monitoring and surveillance of urban airspaces and airspace corridors has become critical. Traditional centralized surveillance systems are limited in their ability to provide comprehensive coverage and real-time monitoring. This paper explores the concept of distributed sensing as a solution for monitoring and independent surveillance of urban airspaces and airspace corridors. We discuss the advantages of distributed sensing, the challenges associated with its implementation, and potential applications in addressing critical infrastructure needs while enhancing airspace safety and management. Additionally, we present an overview of emerging technologies that can enable distributed sensing systems, such as urban air taxis, unmanned aerial vehicles (UAVs), Internet of Things (IoT) devices, and advanced

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data analytics techniques. Finally, we discuss potential future directions and the importance of collaboration between stakeholders to fully realize the benefits of distributed sensing in urban airspace monitoring.

Figure 1. Concept for Future Smart Urban Airspaces

The convergence of urban air mobility with a smart space concept holds promise towards addressing many of the barriers and challenges inherent in realization of advanced UML concepts in a safe and cost-effective manner. As a working concept, smart spaces can be defined as an enabling environment where large-scale networks of inter-communicating technologies are embedded in and distributed throughout the environment, including on mobile devices and mobile actors who are operating within the environment and can take advantage of these resources in real-time towards goals of both the local actors and the global environment [1]-[5]. Technologies may include sensors, actuation, computational capabilities, databases, and advanced services. Smart spaces allow users of the environment to access these shared capabilities in real-time through wired or wireless information technology infrastructure, allowing communication, coordination, and competition between agents as they share technology resources embedded throughout the environment to accomplish their goals. Users of the environment are referred to as smart entities themselves - such as smart cars operating on a smart road – and have the capability to autonomously communicate, analyze, sense and react to objects, hazards, and other operators in the environment.

The Distributed Sensing project at NASA is investigating a smart spaces approach towards addressing the barriers and challenges presented in NASA's vision for future air transportation under AAM and UAM [6]-[9]. Distributed Sensing in a smart space context may enable new capability that can safely increasing the level of autonomy and reliability of AAM vehicles, while improving autonomy that facilitates m:N operations envisioned for advanced UML operations [10]. Uncrewed aircraft operations for AAM at advanced UAM maturity levels involve significant barriers and challenges relating to sensing and perception, particularly due to operation in and around metropolitan city centers. A potential smart space concept envisioned in the Distributed Sensing project may, for instance, consist of an air traffic network of autonomous smart aircraft vehicles interacting with shared resources distributed and embedded through a smart space environment – such as airspace monitoring sensors distributed around a smart vertiport or smart airspace corridor. Airspace monitors and traffic controllers may also utilize distributed sensing capabilities to provide services to aircraft operating in the airspace they are monitoring (e.g., providing air traffic information to aircraft operators) and issuing coordination information (e.g., separation assurance services, vectoring instructions, or sequencing instructions for takeoff and landing at a vertiport). Third-party service providers may also be users in this environment, providing real-time sensing or analysis services to other users. For instance, third-party services may provide detailed weather and turbulence maps to vehicles or fleet operators that are updated from sensors distributed both around the environment and relayed from instruments onboard aircraft that are currently in flight. A concept drawing for a future airspace is illustrated in Figure 1, from [11].

II. Needs and Challenges for Future Urban Airspaces

The needs and challenges for urban area airspace operations have been outlined in many previous studies [12][13]. For this publication, we highlight some of the relevant issues that are challenging for current technology and can be addressed through a distributed sensing approach, as illustrated in Figure 2.

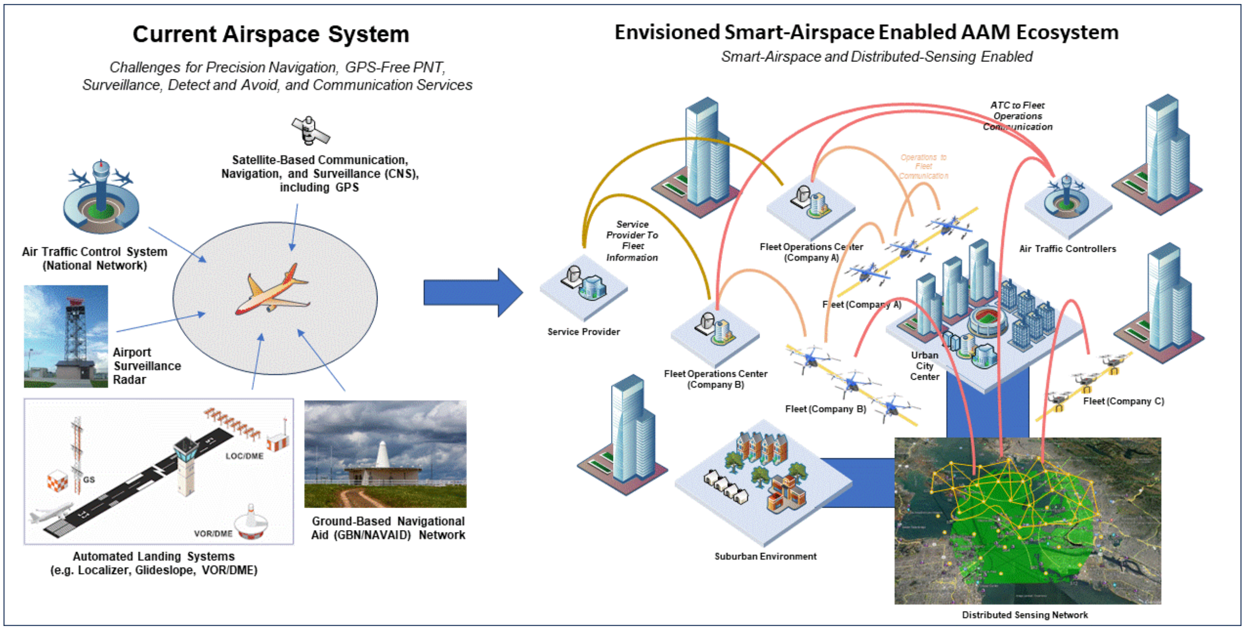

Figure 2. Challenges of Current Technology for Future Urban Smart Airspace Systems

A general challenge for urban operations, which extend from the ground level in an urban canyon to above buildings and the urban canopy, is associated with operations of RF-based systems in this environment, particularly for localization, surveillance, and communication. Legacy aviation systems [14][15], such as the system of NAVAIDS, radar surveillance, navigation systems such as automated landing systems, and satellite-based navigation systems such as and GPS, will be challenging to utilize in these environments due to issues such as interference and clutter. Ground to air communication with aircraft [16][17][18], traditional radar systems for surveillance, and traditional navigation/landing systems are also challenging to utilize in these environments [19][20][21].

Challenges with scaling present additional issues in applying current technologies to urban mobility. UAM concepts move beyond the assumption of largely isolated aircraft with an onboard pilot onboard that is separated from other vehicles by distances measured in nautical miles. Additionally, the current assumption for aviation assumes the airspace is clear of obstacles (clear-sky assumption). Concepts for future urban airspaces envision hundreds or thousands of vehicles operating within a small and cluttered environment. The distances between vehicles and obstacles will be on the order of meters rather than nautical miles. Scaling also presents challenges the current centralized air traffic control model, as well as communication systems such as ADS-B, which become saturated when applied to traffic systems of this size.

Additional challenges are presented by the complexity of the urban airspace environment, as compared to current airspaces. Assumptions of a clear sky environment will no longer be valid, as urban airspaces will be cluttered and densely packed with obstacles and hazards. Regional weather measurements move from a regional level to a localized level to capture the micro-weather patterns and phenomena that exist in the urban setting.

The transition from onboard pilots to automated pilotless vehicle and m:N operations for fleet management present additional challenges. The lack of onboard pilots reduces situational awareness and response times, impacting nominal operational tasks as well as off-nominal tasks to address anomalies on onboard failures.

The transition of the operational environment into a densely trafficked urban environment is further challenged by the reduction in the ability to control the airspace as compared to existing airspaces. The number of vehicles envisioned will inundate currently used methodologies for air traffic control. Further, the urban environment is less controllable from a regulatory standpoint. For instance, new buildings or constructions may arise at any time that propose new challenges for air traffic, which may introduce new obstacles into the airspace, impact to local weather patterns, effect wireless communication and interference, and may block or occlude ground-based sensor systems.

III.Application Focus Areas

This study is currently focusing on applications of distributed sensing to the following use cases in support of urban airspace monitoring and operations.

- Airspace monitoring, surveillance, and conformance monitoring in (1) vertiport terminal area and (2) airspace corridors

The complexity of urban airspaces challenges traditional systems for airspace monitoring. The presence of high-rise buildings as large metallic obstructions in the urban canyon makes utilization of a single radar surveillance system difficult. The challenges with RF interference render GPS-dependent methods such as ADS-B less effective. Currently, no viable system has been identified that can provide independent airspace monitoring for urban environments that satisfy our feasibility study requirements (which includes requirements for 1 meter accuracy or greater, updated at 1 Hz or greater), with can also provide necessary services for situational awareness of the airspace, such as object/vehicle identification, classification, and tracking. Several candidate sensor modalities are being evaluated in this research, as described in the sensor selection discussion below. Two general locations for monitoring are considered in this study: (1) vertiport terminal area monitoring, and (2) airspace corridor monitoring.

- Precision Navigation, Precision Approach and Landing (PAL), and GPS-Free Position Navigation and Timing (PNT)

The requirements for providing vehicles with a system for reliable and accurate localization and navigation is similar to the airspace monitoring application, with the addition of more stringent location estimation accuracy, latency, and frequency updates. For this study, we require localization inputs be available for incorporation into a navigation solution being utilized onboard for real-time guidance, navigation, and control of the vehicle. This study requires submeter accuracy in the localization estimate at minimum frequency of 10 Hz. The requirement for onboard consumption further challenges a distributed sensor network solution by requiring time-critical and safety-critical signals being communicated over wireless ground-to-air links, which for instance impose more significant bandwidth constraints.

- Distributed detection of airborne hazards, including detect-and-avoid (DAA), separation assurance (SA), and collision avoidance (CA)

The requirements for monitoring of the airspace for airborne hazards in the near proximity to air traffic for the purposes of DAA, SA, and CA are similar to the applications for airspace monitoring and navigation. However, the unique challenges for DAA, SA, and CA add additional requirements and constraints to the services. End-to-end functional with control services in the loop must be verified and validated. The specific selection of DAA/SA/CA methodologies in future urban airspace traffic management is still an open subject for research, and this selection will impact the requirements for a distribute sensor network to support these services. Additionally, the distributed sensing network provides the means for decentralized vehicle-to-vehicle methods to be instantiated, providing adaptive communication structures to be instantiated to share time-critical information between cooperative vehicles.

- Distributed detection of large-scale environment monitoring and weather hazards

The complexity of the airflow around urban structures adds additional hazards for future urban air traffic beyond what is faced by current commercial air traffic. Micro-weather conditions are a known hazard for current urban air traffic, such as helicopters, with such dangers from such phenomena as vortices and circulation around buildings, near elevated helipads, interaction between rotors and nearby obstacles, localized turbulence, and localized weather hazards such as cloud and fog banks. A distributed sensor network can utilize sensors like LIDAR, cameras, and radar to gather real-time data on weather, obstacles, and traffic flow. This data can be processed and shared between systems to maintain a dynamic picture of the airspace. The urban airspace is also characterized by often unpredictable weather conditions and localized weather conditions, which might impact weather operations. Distributed sensing can provide a fine-grained real-time weather map by integrating data from ground sensors, airborne sensors, and even by the behavior of the vehicles themselves. Services can include microclimate detection, where sensors can track sudden wind gusts, temperature shifts, or precipitation changes in localized areas, providing hyperlocal forecasts. Additionally, this application can support adaptive routing services, where real-time weather data would allow the system to adjust routes dynamically to avoid dangerous zones, similar to how aircraft avoid turbulence or storms, but at a finer resolution supporting the urban environment.

- Distributed airspace traffic monitoring, traffic control, flow management, and m:n fleet operations management (e.g, autonomous separation, autonomous sequencing and spacing)

Distributed sensing networks can continuously monitor local traffic density and relay real-time updates to air traffic management systems, in a centralized control strategy, or directly to the vehicles and operators in a decentralized strategy. Algorithms can dynamically adjust flight paths or prioritize critical missions to deconflict congested airspace. Potential systems work similarly to adaptive traffic control for cars but with the added complexity of three-dimension movement. Distributed traffic monitoring could also leverage predictive models to foresee bottlenecks based on current trajectories and reroute before issues arise. Decentralized traffic strategies can be formulated that would share information between vehicles and vertiport air traffic controllers to automate services such as sequencing of vehicles into the approach path for landing at vertiports, and automatically maintaining spacing and separation between air traffic on a peer-to-peer basis, with the responsibility assigned to the vehicles rather than assigned to a centralized traffic control coordinator.

- Distributed acoustics sensing and noise monitoring.

A proposed application for distributed sensing is for monitoring of vertiport noise levels, detecting potential equipment failures, or localizing aircraft based on sound. Environmental noise may be of concern to urban air space operations, with local limits or concerns near vertiports or along heavily-trafficked corridors. Distributed arrays of acoustic sensors can provide awareness and monitoring of localized noise impacts on various metropolitan areas. Additionally, acoustic sensors could provide data to identify pending failures or anomalies in the aircraft, such as unusual rotor noise that may be indicative of a propulsion system failure. Acoustic sensors may also assist in localization and classification of aircraft, particularly when coupled with other sensing modalities, providing additional information for situational awareness of the air traffic in a local area.

- Onboard aircraft sub-system sensor networks

Given time and resource constraints, these applications are not being pursued within the scope of this initial feasibility study. There are several current and future applications for distributed sensing onboard the aircraft. Such applications as distributed structural monitoring of flexible wing structures, distributed propulsion sensing, distributed microphone and acoustic arrays and vibration sensors monitoring passenger noise and ride comfort, distributed air flow monitoring of airflow around a fuselage or wing, and distributed monitoring of electrical systems.

- Intelligent vehicle/fleet health and safety management; Air traffic network health monitoring, management, and prediction.

Given time and resource constraints, these applications are not being pursued within the scope of this initial feasibility study. There are many potential future applications and services that can be derived from combining historical information collected onboard the aircraft with historical data collected across the entire sensor network. Large-scale data processing, machine learning, and artificial intelligence techniques would take advantage of this information to identify past trends and predict future forecasts to assist in the management of vehicle fleets, such as adjusting routes to optimize taxi service locations, or assisting in the ongoing management of air traffic flow to achieve desired flow patterns, reduce localized congestion, or increase performance and throughput.

IV. Programmatic Objectives

The following are the objectives for this preliminary investigation into distributed sensing and smart urban airspaces, as illustrated in Figure 3.

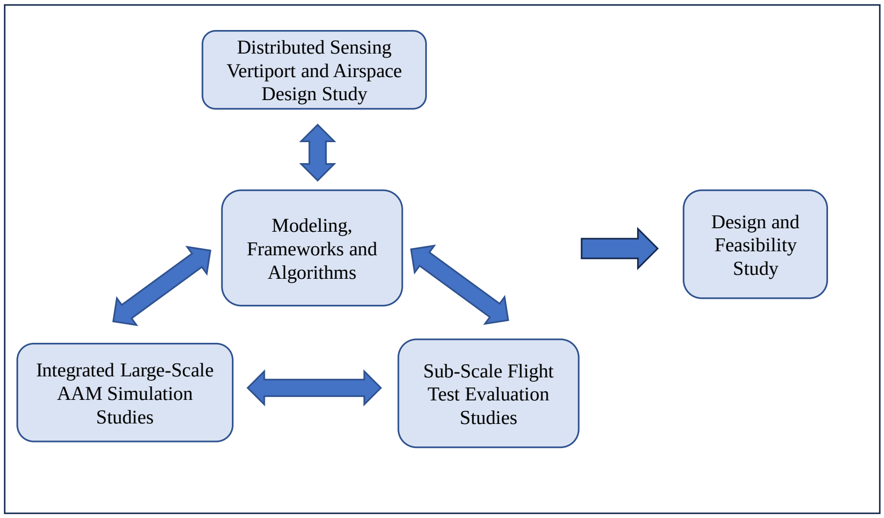

Figure 3. NASA's Distributed Sensing Project Research Approach

This effort focuses on developing a system design study and feasibility assessment in this preliminary phase investigation. This effort focuses on the technical aspects of this concept, including developing mathematical formalisms and proofs to model major elements of the proposed system, and to prove this system can work as intended. Success in this phase will pave the way for future regulatory discussions. This project will start with frameworks and formalism, developing prototype algorithms and hardware system for the purposes of this evaluation. The system design and prototype technologies will be evaluated in large-scale simulation studies and sub-scale flight experiments. These experiments will measure feasibility using a set of performance metrics to assess performance and reliability. Key elements of this effort are described below.

- Conduct a conceptual design study for distributed sensing in smart urban airspaces.

This project is conducting a design study to perform an initial assessment of distributed sensing on how it may impact future urban airspaces. It includes identifying high level stakeholders, challenges concerns, applications, use cases, and requirements while performing a high-level conceptual design. Current status towards this effort are summarized within this paper.

- Perform a feasibility assessment of the concept design, including experimental evaluation against performance metrics.

This research will assess the feasibility of distributed sensing concepts as embodied within the design study. This objective includes developing performance metrics that can be objectively measured to analyze feasibility. Experimental evaluation will be performed in simulation and flight experiments, the development of which is described in supporting elements below.

- Develop (1) mathematical frameworks, (2) concept architectures, and (3) algorithms for incorporating geographically distributed (non co-located) sensors and remote observations of opportunity that enables topologically adaptive control and estimation structures in a smart-airspace environment.

Supporting the conceptual design and feasibility studies, this element will develop the necessary mathematical frameworks, concept architectures, and algorithms to the level needed to meet the goals of an initial feasibility study. This effort will be focused on (1) establishing baseline end-to-end functionality, and (2) investigating high-level critical barrier challenges. For experimentation, a baseline end-to-end system is needed that can minimally provide simulation or flight test experiment results. Additionally, high-level critical-barrier issues need to be addressed, such as a methodology for adaptive estimation, which is critical to providing models and mathematically rigorous proof of operation for the system.

- Develop simulation prototypes and test in large-scale high-fidelity UAM simulations.

Effective feasibility evaluation of this concept requires implementing and testing a prototype system in large-scale simulations that can evaluate the performance of this concept at a relevant scale. Towards these ends, this effort is developing an appropriate large-scale simulation system to simulate air traffic over a metropolitan area. The details of this simulation system are described in the following sections of this paper. Additionally, the supporting tools and technologies developed for this evaluation will also be delivered to other NASA projects and made available to external stakeholders.

- Develop and evaluate hardware prototypes on sub-scale vehicles for flight test evaluations.

In addition to simulation, hardware prototypes of various distributed sensing technologies will be developed and tested in small sub-scale flight test experiments being conducted at NASA. Opportunities for full-scale flight testing with stakeholders will also be pursued.

- Establish a roadmap for future activities towards realization of this concept.

The final objective for this project is to outline a roadmap towards advancement and realization of these concepts based on results and findings from the preliminary design and feasibility studies. This effort seeks to propose a roadmap towards continued maturation of these concepts with relevant stakeholders both within NASA and within the larger aviation community. This element involves coordination with stakeholders that include industry, academia, other government agencies, and standards bodies.

V. Development Phases and Progress

The following phases describe the progression of this effort.

Phase 1 – Foundations and Proof of Concept:

The initial phase of this effort focuses on laying the groundwork for adaptive networks in dynamic airspace. Initial research will concentrate on understanding the core challenges of network reconfiguration, bandwidth allocation, and vertical zone communication. Small-scale prototypes will be developed to test basic concepts, ensuring that the system can adapt to fundamental network changes. These prototypes will be tested in simulated environments to evaluate how the mesh network responds to aircraft movements and varying ground station conditions, establishing baseline performance metrics for the system.

Phase 2 – Integration and System Expansion:

In the second phase, real-time flight data will be integrated into the system, alongside initial test flights, to observe how the network adapts to changing conditions in real-world scenarios. The focus will be on testing adaptive routing algorithms and dynamic bandwidth allocation. As the system matures, testing will expand to include communication systems in vertiports and other high-traffic and addressing fundamental challenges unique to these spaces.

Phase 3 – Optimization and Resilience Testing:

The third phase shifts focus toward optimizing the system’s performance. Algorithms will be refined for faster reconfiguration and more efficient use of available bandwidth. Testing will also address system resilience, evaluating how well the network can recover from failures such as lost communication links or sensor malfunctions. Redundancy strategies will be implemented and tested to ensure continuous operation. Scalability assessments will be conducted in larger simulated airspace regions to assess the system’s capability to handle full-scale airspace operations.

Phase 4 – Integrated Testing and Assessment Finalization:

In the final phase, full-scale and end-to-end testing will be conducted, involving multiple aircraft and a more extensive ground network setup. These systems will be integrated into larger evaluation frameworks for air traffic management and humans in the loop. This will allow for an in-depth assessment of the system’s overall performance in simulated operational environments. Assessment for compliance will outline the path by which these systems can meet regulatory requirements in preparation for certification supporting manned aviation. Additionally, human factors testing will evaluate the usability of the system, ensuring that the data is presented in a way that is both actionable and understandable for operators.

Phase 5 – Transition and Future Roadmap

Collaboration with regulatory bodies, aviation stakeholders, and urban planners will be an essential next step towards advancement of these concepts. A roadmap will be developed that will outline the roles and responsibilities of various organizations in this process. The path towards certification will be outlined, setting clear benchmarks for system reliability, precision, and availability, and aligning with standards like DO-178C (software certification) and DO-254 (hardware certification), and propose validation and certification methods to ensure compliance with safety standards. The roadmap proposes a phased approach towards advancing these technologies. External stakeholders will be engaged to analyze the results of this effort and validate the result of this study.

VI.Criteria and Metrics for Feasibility Assessment

Initial efforts for assessment will include performance metrics, such as evaluating tracking and localization accuracy. Metrics for this assessment are being derived from the use case and simulation scenarios under development. Additional criteria for evaluation will be considered as the study and project progresses to more advanced stages. The proposed criteria are described below.

System reliability and availability are essential criteria for assessing the system's ability to function continuously without failure, especially in real-world operational conditions. This metric evaluates the system's uptime and how well it handles full-scale operations under varying traffic densities and environmental stressors.

Latency and timing are key factors for real-time decision-making. These metrics measure the speed at which the system can process data, respond to changes in airspace conditions, and issue updates or alerts. Minimizing latency is crucial to ensure timely actions, particularly in dynamic or high-risk situations.

Sensor fusion performance and data integrity refer to the system's ability to integrate data from multiple sensors seamlessly. This includes ensuring that the combined data output remains reliable and consistent, even when some sensors provide noisy or incomplete information. Effective sensor fusion ensures accurate situational awareness despite potential sensor errors or data gaps.

Scalability evaluates how well the system adapts as the number of aircraft and sensors increases. Metrics in this criteria assesses both processing capacity and the communication network's ability to handle the greater data volume and traffic without significant performance degradation.

Bandwidth and data throughput are critical for determining how much data can be transmitted within the system. As airspace becomes more congested, it is important to track whether the communication system can support the required data volume, particularly in high-density environments where bandwidth demands are high.

Safety and fault tolerance measure the system's ability to detect, respond to, and recover from faults. This includes failures in sensors, communication links, or processing units, evaluating how well backup systems and redundancies can take over seamlessly to maintain continuous operation.

User interface and decision support are crucial for evaluating how effectively air traffic controllers or other users can interact with the system. This metric assesses the clarity, usability, and efficiency of the interface, ensuring users can make timely and accurate decisions based on the information presented.

Finally, environmental and weather adaptability examines how well the system performs in various weather conditions. Since adverse weather, such as low visibility, turbulence, and extreme temperatures, can significantly impact air traffic, evaluating the system's performance under these conditions is essential for ensuring its robustness and reliability in real-world operations.

VII. Airspace Design Study and Concept of Operations

A large-scale simulation environment has been developed for experimentation and evaluation to achieve the objective of performing a feasibility assessment for this concept. The generalized architecture for this system is shown in Figure 4. Additional details can be found in [22] and [23].

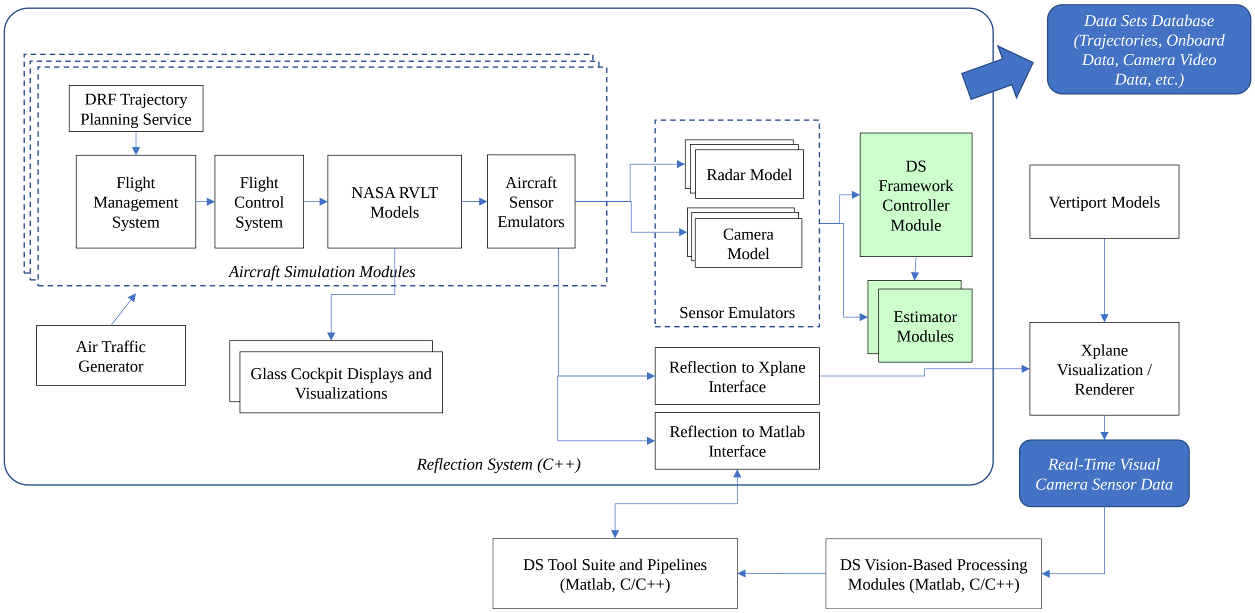

Figure 4. Large-scale Regional Urban Area Simulation Environment

The simulated environment and use-cases developed for the feasibility assessment simulate a large regional area that includes portions of the San Francisco and Oakland metropolitan areas. This simulated environment includes two urban centers and spans approximately 1000 square kilometers (around 400 square miles). This environment simulates twenty vertiports. The current implementation simulates 50 vehicles at any given time and is being expanded to 100+ vehicles as part of this effort. A growing network of ground sensors, currently at around 200 but expected to grow to 1000+, has been designed and integrated into this simulated environment, servicing vertiports and corridors in this simulated network. The diagrams in Figure 5 show an initial and preliminary layout for some of the vertiports, corridors, and sensor network locations.

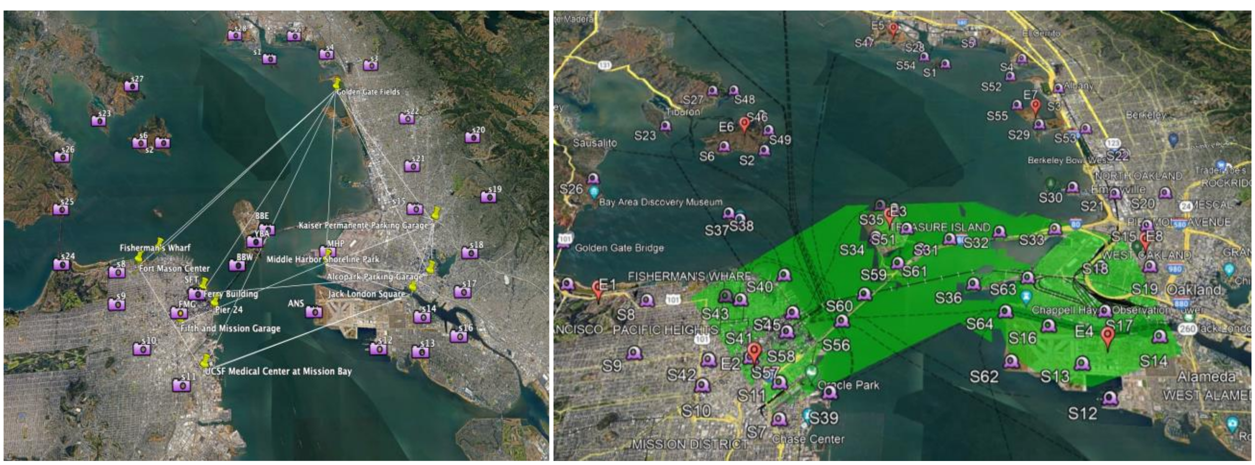

Figure 5. Simulated AAM regional environment. *Figure shows preliminary vertiports, corridors, and a sensor network used in earlier phases of this effort (left), and an expanded sensor network system (right).*

This simulation utilized several assumptions to simulate a relevant traffic network at the scale needed to assess feasibility. A network of air traffic corridors, approach paths, and departure paths around each vertiport was developed to provide sufficiently complex traffic, as shown in Figure 6.

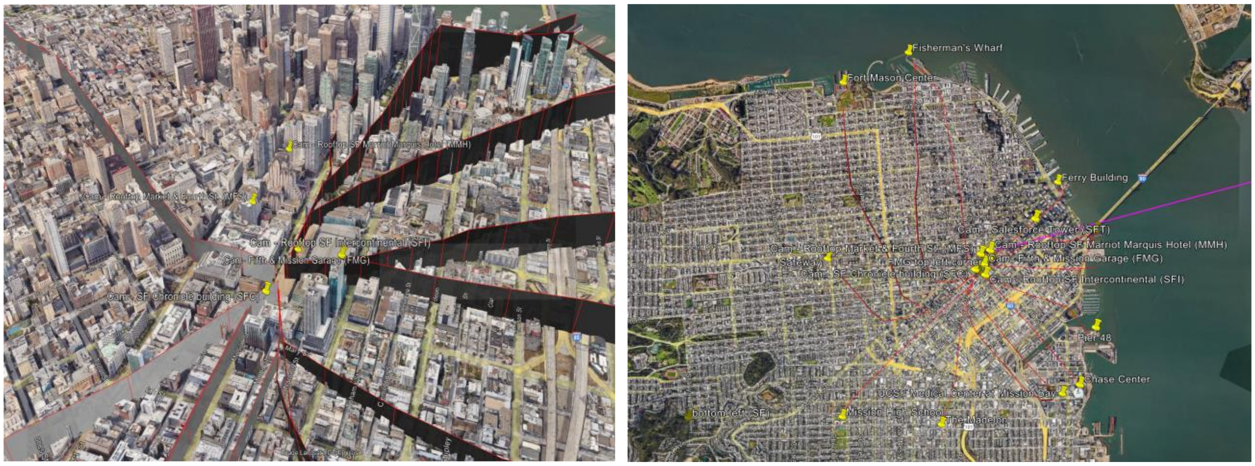

Figure 6. Corridors and Airspace Design Concepts. *This study developed approach and departure path concepts (left) and vertiport-to-vertiport corridors (right) to simulate traffic complexity***.**

This system can generate offline high-fidelity visual camera renderings for onboard aircraft sensors and ground sensors, as shown in Figure 7. For real-time experiments, lower-fidelity sensor models are employed to capture the sensor behavior, for example, by replacing the detailed target detection and tracking pipeline developed for a single imager with a lower fidelity model that captures the main characteristics of this system.

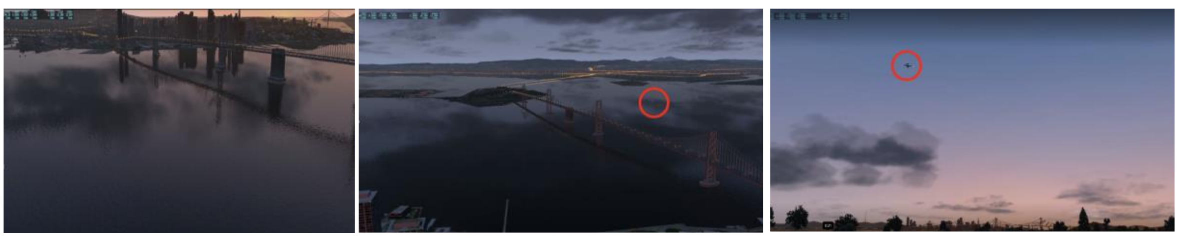

Figure 7. Renderings for Simulation of Varying Conditions of Visual Sensors. *This figure shows visual onboard imagery (left), building-top level sensor imagery (middle), and ground-level sensor imagery (right).*

VIII.Vertiport Design Study Considerations

This study is currently examining the design and layout of candidate sensor network that support vertiport area applications in the simulation. For instance, Figure 8 shows the layout of a proposed sensor network comprising visual range cameras, IR cameras, ground radars, and lidar, providing coverage along one approach/departure path to this vertiport. These sensors have been simulated and integrated into the simulation environment to experiment with surveillance and precision approach and landing control through the distribute sensor network. A simulated vertiport system of visual and infrared landing lights has also been developed, as shown in Figure 9. Studies using the high-fidelity rendering (offline) and lower-fidelity models were conducted and are described in [24] and [25].

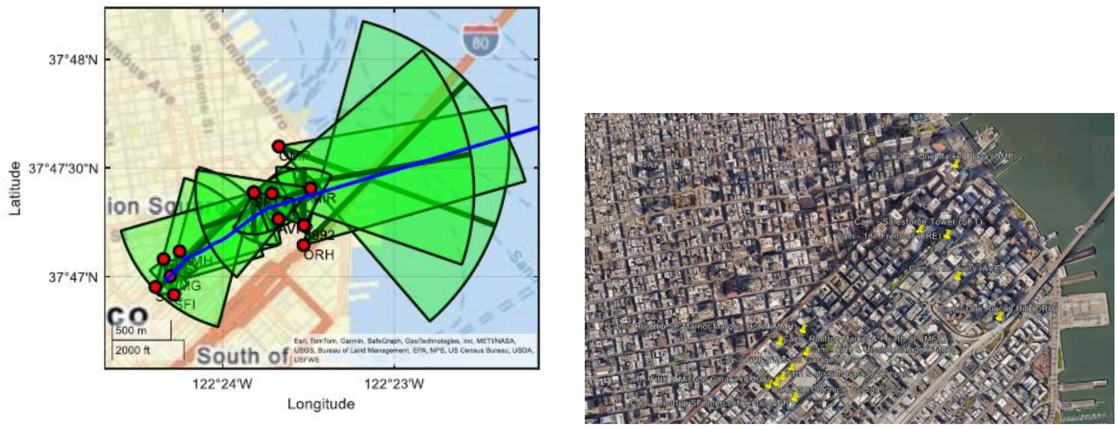

Figure 8. Sensor Network Coverage for Vertiport Operations. *Sensor layout for an approach/departure path (left) and location with satellite overlay (right), showing challenges with obstacles and coverage from ground-based sensors in an urban environment.*

Figure 9. Vertiport Design and Simulation. *Showing simulated landing light pattern design at the vertiport (left) and approach light pattern along the building top (right).*

IX. Sensing Modalities

Various sensing modalities are being explored in this investigation to address diverse requirements in aviation operations, particularly in urban environments. These include the following sensors, which summarize general sensor capabilities, limitations, and describe supporting use cases being considered in this study. This represents many of the sensors currently being evaluated in this project, but this is not a comprehensive list.

Lidar (Light Detection and Ranging) is one such technology, offering highly-accurate 3D mapping for obstacle detection, often as a point clouds, along with doppler velocity information. When used on vehicles, Lidar facilitates precise localization, terrain modelling and hazard detection in the near vicinity. Furthermore, in conditions where particulates are present in the air, Lidar can measure airspeed and monitor circulation or vortices, such as trailing vortex detection. Practical applications include aiding in localization for precise navigation, detection of hazards and obstacle, creating detailed maps of vertiport environments, and monitoring movement of objects and humans on the vertiport surface. However, Lidar faces limitations such as reduced efficacy in adverse weather (fog or rain), challenges with certain materials (e.g., glass or water), short range for large-scale airspace monitoring, and susceptibility to obstruction by solid objects.

Infrared and thermal sensors present another promising option, particularly effective in low-light or visually degraded conditions like fog and smoke. These sensors can detect the heat signatures of aircraft, ground vehicles, and humans. Additionally, infrared sensing can provide precise navigational cues. Integration of infrared beacons on aircraft enables ground-based or airborne thermal sensors to track and detect movements, enhancing situational awareness and precision navigation. Integration of beacons on ground installation, such as a vertiport landing light system, can provide robust and precise navigational cues for aircraft. Despite their advantages, these sensors are limited by their shorter range and lower resolution compared to visible-range imaging systems.

Acoustic sensors complement these technologies by detecting environmental sound patterns and vibrations. As part of a distributed sensor network, they can assist in identifying nearby aircraft, detecting mechanical anomalies, and monitoring noise levels in the areas surrounding vertiports and airspace corridors. They are also useful in equipment failure detection and aircraft localization. However, acoustic sensors are sensitive to environmental noise interference and have limited operational range, which can restrict their effectiveness.

Visual range camera systems provide rich spatial detail and contextual information, making them cost-effective and versatile. They support airspace monitoring, obstacle detection, collision avoidance, and decentralized traffic control. However, their performance is highly dependent on environmental conditions, such as lighting variations, adverse weather, and visibility, and they require substantial processing power and calibration.

Radar sensors are widely used for ground-based surveillance, offering robust ranging, velocity, and depth information even in adverse conditions. Their capabilities include long-range operation, doppler velocity measurements, and wide field-of-view coverage. They are well-suited for airspace monitoring, proximity alerts, and traffic management. Nonetheless, radar struggles in urban environments due to clutter, limited resolution, and susceptibility to interference, including noise and jamming.

Inertial Measurement Units (IMUs), magnetometers, and barometers are traditional navigation sensors commonly on today's aircraft. IMUs provide acceleration, orientation, and velocity data, supporting navigation corrections in a standard strapdown navigation solution and dead-reckoning. However, they are prone to drift over time without external corrections, and the gravity field must be disambiguated from accelerometer measurements. Magnetometers offer heading and orientation information relative to magnetic fields but are sensitive to interference from surrounding metal objects and from electronics. Barometric Pressure Sensors are simple yet reliable tools for altitude estimation, often used in navigation and altitude maintenance. However, their sensitivity to weather fluctuations necessitates frequent calibration. Typically, these sensors are fused together using methods such as an extended Kalman filter along with an external localization estimate to provide a consistent navigation solution onboard the aircraft.

Ultrasonic sensors are effective tools for short-range object detection, particularly in cluttered or complex environments. These sensors utilize sound waves to identify nearby objects and measure distances, making them well-suited for applications such as automated docking, vertiport ground operations, and near-ground altitude estimation during landing, and close-range obstacle detection. Their ability to provide precise ranging estimates provide general utility in close-proximity operational scenarios. However, ultrasonic sensors have a relatively short operational range, which restricts their use to specific environments. Additionally, their performance can be adversely affected in high-noise settings where background vibrations or sound interference may reduce accuracy and reliability.

Environmental sensors can measure wind speed, temperature, humidity, and air quality in real-time, contributing to weather modeling, flight path planning, and vertiport safety. While useful, these sensors often provide highly localized data and are prone to interference from ground-level conditions, limiting their broader applicability in urban environments. Integrating these sensors into a distributed sensing network could significantly expand their capability, enabling broader monitoring and predictive analysis of weather across larger areas, including regions characterized by complex and localized weather patterns.

Active Radio Frequency (RF) localization employs active transceiver systems to determine positions and movements through techniques such as time-of-flight (ToF), angle of arrival (AoA), or signal strength measurements. These systems provide wide-area coverage over long distances with high temporal resolution, offering frequent and precise measurements. They are resilient to most weather conditions and can scale effectively for use with numerous aircraft. Furthermore, their accuracy and adaptability can be enhanced through network design, making them a standard method for localization in distributed sensor networks. Practical applications include airspace monitoring, aircraft localization, collision avoidance, precision navigation, and dynamic airspace adaptation. These systems may assist in managing vertiport ground assets, enabling precise approaches and landings, and supporting search and rescue operations. However, active RF localization systems face challenges such as susceptibility to interference and noise, including intentional jamming. They also encounter limitations related to bandwidth, signal blockage, energy consumption, infrastructure demands, and regulatory constraints surrounding spectrum usage.

Passive Radio Frequency (RF) sensing differs in that it detects signals from other aircraft or communication systems without emitting signals itself. This passive approach enhances stealth and energy efficiency while minimizing electromagnetic (EM) interference with other RF operations. Passive RF sensing is particularly useful for monitoring airspace by detecting and triangulating the positions of other transmitters, as well as managing spectrum usage in complex environments. However, these systems require meticulous calibration to ensure accuracy and are susceptible to interference from other RF sources, which can complicate their deployment and operation.

X. High-Level Operational Phases and Requirements

Towards development of a general framework for distributed sensing, the research in [26] builds on the concept of smart spaces, where sensing, processing, and communication are embedded throughout the environment, and users operating within the space can exploit these capabilities in real-time through collaborative information sharing networks. Building from these concepts, the authors present a framework to enable a dynamic, topologically-adaptive, and distributed estimation system for man-rated aviation to address challenges faced by autonomous AAM operations. This paper presents the initial concept of operations and system design for this framework, provides a mathematical formulation for abstraction of the problem, identifies requirements and constraints for operation, and presents algorithmic constructs and mathematical formalisms to demonstrate operation. The proposed framework is currently being evaluated in simulation on a regional AAM operations system and will focus on two initial applications: (1) GPS-free navigation supporting precision approach and landing (PAL), and (2) surveillance and conformance monitoring of aircraft in vertiport airspaces. Such approaches show promise in addressing gaps in current technologies needed to enable future AAM concepts, while promising greater capabilities, performance, robustness, and safety over current aviation systems and operations.

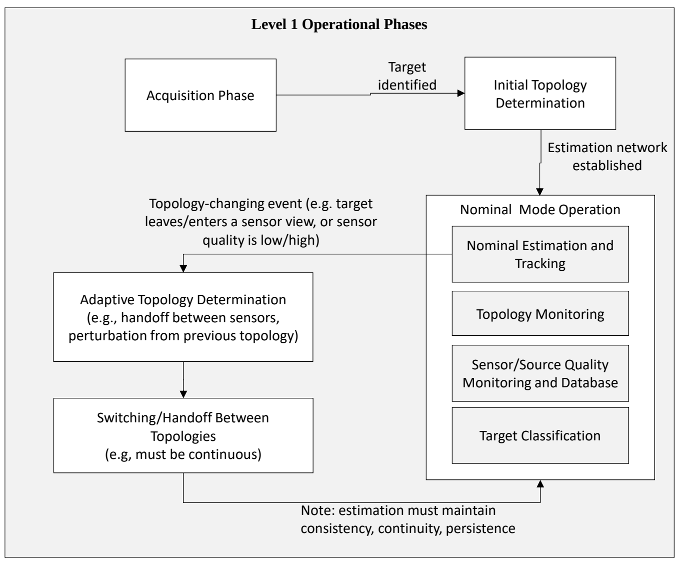

Figure 10. Framework Operational Phases

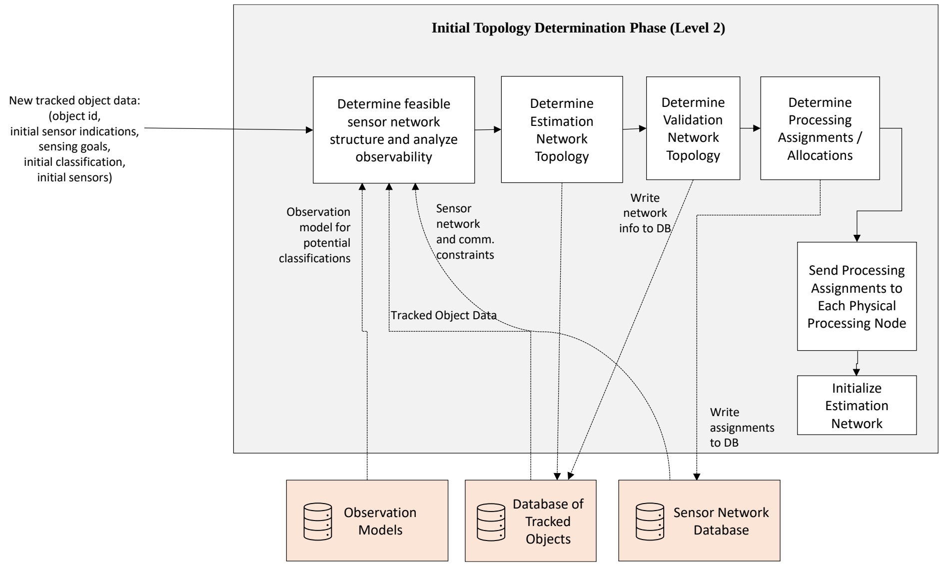

Figure 11. Topology Determination Phase Diagrams

The general operational phases of the framework are shown in Figure 10. This model guides the framework through various operating modes supporting the surveillance use case. When a potential target is identified in one or more sensors, the acquisition phase identifies the target as an entity to be estimated and confirms the target. The initial topology determination phase specifies an initial distributed sensing network topology over various elements in the airspace that meets the requirements and estimation goals while satisfying constraints. Once the topology has been established, the system enters a nominal operational mode. During nominal operation, the target state estimate is updated at each time-step based on updates from the sensors. Asynchronously, the framework performs three other functions. The framework monitors the current network topology to identify any event that would require a topology change, such as the target vehicle leaving a sensor volume, loss communication from a sensor, etc. Additionally, the framework provides continual quality estimation across all sensors with overlapping observation of the target through cross-validation of each sensor with the consensus. While the target is estimated in the specified estimation network topology, the system will perform target classification to help classify the target for the consumers of the estimate. For instance, determining if the target is a sUAS, an eVTOL, a helicopter, or a bird will be useful information for airspace operators and for onboard detect-and-avoid functions. The functional modes of operations in Figure 10 represent the major ‘Level 1’ operational modes. Additional details of the framework can be found in [26]. Investigations into automated calibration and registration across distributed sensing networks were considered in [27]. Classification methodologies were investigated in [28] and [29].

XI.Airspace Design Study Considerations

The selection and placement of sensors integrated into a distributed network requires consideration of a few issues, including accuracy needs, redundancy needs, complementary strengths, desired maximum service performance with communication constraints, and environmental constraints. Redundancy of sensors assists in ensuring operational reliability and availability. The complementary strengths of the selected sensors can be considered to provide adequate performance across varying conditions and to assist in providing enhanced performance. For instance, pairing radar (robust ranging information) with vision (contextual information) provides more information for airspace monitoring and assists in multi-sensor tracking, as described in [30]. A layout of a proposed configuration is shown in Figure 5. Results from an initial case study are presented in [31].

Network utilization in a real-time assessment is currently being evaluated in the simulated traffic environment. For instance, initial results from simulation are shown in Figure 12. This figure shows a snapshot of network sensor selection, communication path selection, bandwidth utilization, and overlapping information flow structure supporting four of the users of the network providing observational coverage of the region. More details of this experiment are described in [32], [33] and [34].

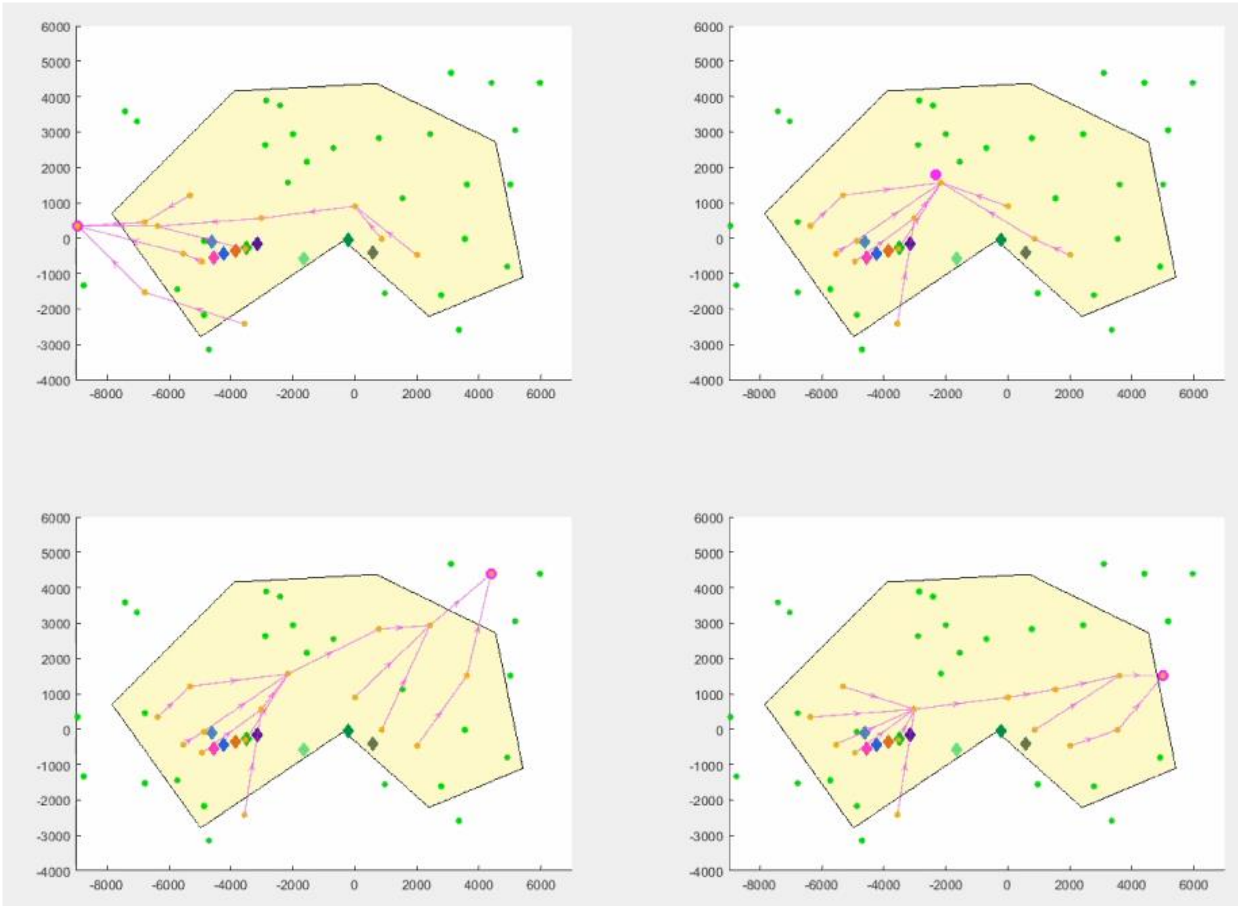

Figure 12. Network communication structure and local information flow. *The figure shows communication flow between ground and air nodes supporting four different consumers (top-left to bottom-right), estimating selection of sensors, selection of communication routes, and bandwidth usage over the shared network paths.*

An adaptive extended Kalman filter design is being developed to provide continuous observations of the target objects that maintain consistency across topological changes. An example result for tracking of a single aircraft is shown in Figure 13. Additional details of this research are described in [35] and [36].

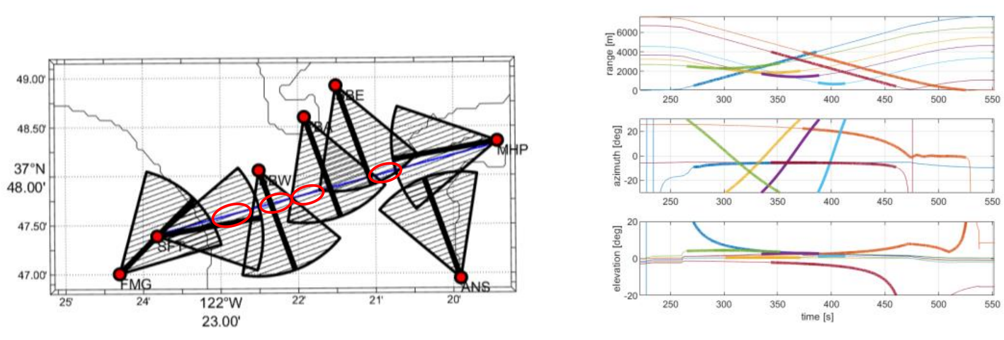

Figure 13. Continuous estimation of a target between sensor coverage regions. *The layout of sensors and coverage along a single aircraft track (left), the local observation model output (right) highlighting usable sensor readings and sensor selection in bold.*

In addition to bandwidth limitations and communication topology constraints, satisfaction of performance requirements, such as accuracy and consistency of estimated aircraft states along flight paths, are additional requirements for sensor network design considerations. Contributing factors include 3D geometric considerations on estimation accuracy, sufficient overlap within selected sensor sets, the effect of sensor availability on estimation accuracy and stability, and sub-optimal sensor selection with considerations for communication and bandwidth limitations. The resulting optimization topology under constrained optimal sensor selection can be complex, as shown in Figure 14. Additional details can be found in [37].

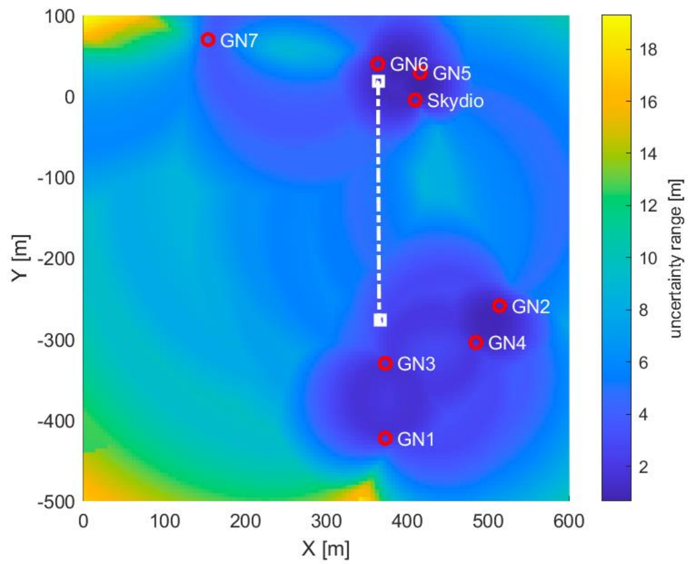

Figure 14. Optimal locations and accuracy topology for a given flight test configuration.

XII. Sensor Fusion Topologies and Pipelines

This effort is currently investigating processing pipelines for estimation and data fusion requirements in simulation and in the hardware prototypes. One of the pipelines developed for deal-time simulation is shown in Figure 15 and detailed in [38].

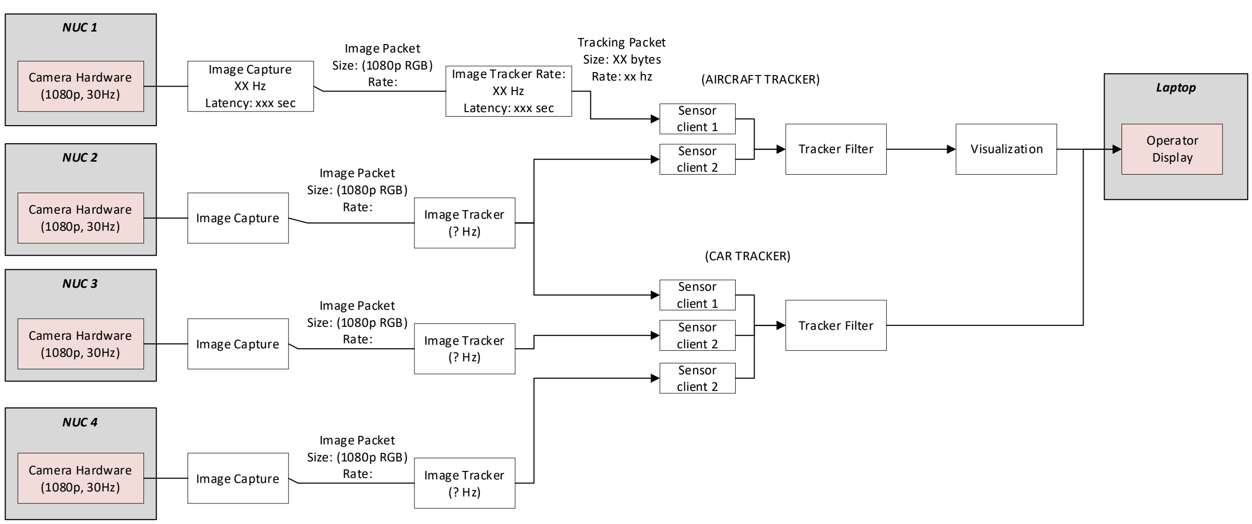

Figure 15. Processing Topology and Pipeline – Ground-Based Visual Observation Network

The selection of sensor pairing that provides complementary observation information is another important factor to considering in the sensor network design and placement problem. One example of this research is investigating is sensor fusion between radar and vision-based camera systems. These two sensor types provide complementary but fundamentally different data. These modalities have complementary strengths - radar excels in range and velocity measurements, even in low visibility, while vision provides rich spatial and contextual information but suffers from a number of issues, such as changes in environmental lighting. Some initial results of this research are shown in Figure 16. Details of this research are provided in [30] and [39].

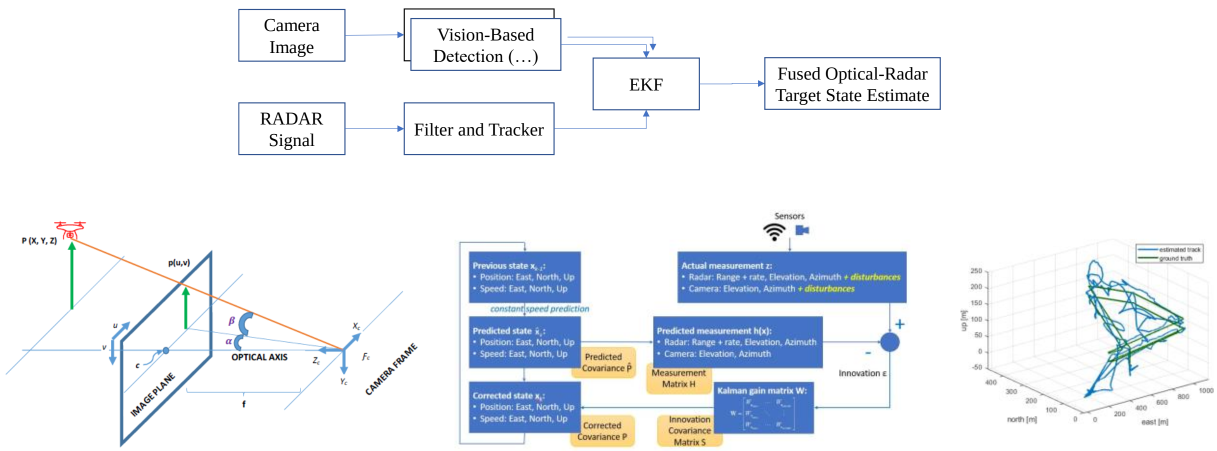

Figure 16. Processing Topology for Optical-Radar Target Detection and Tracking. *Processing pipeline for EKF fusion (top), geometric setup (bottom left), EKF processing details (bottom middle), experimental results from flight text experiment (bottom right).*

XIII. Precision Navigation through the Distributed Sensor Networks

This project is currently investigating alternative approaches to provide real-time control and navigation solutions to allow for precision approach and landing of vehicles in the vertiports through the distributed sensor network. Some preliminary results from precision navigation experiments with onboard lidar and vision system are shown in Figure 17. These investigations include utilization of onboard lidar [40], onboard vision as summarized in [24] and [25], and integration of the onboard sensors with distributed ground-based sensor network observations [41].

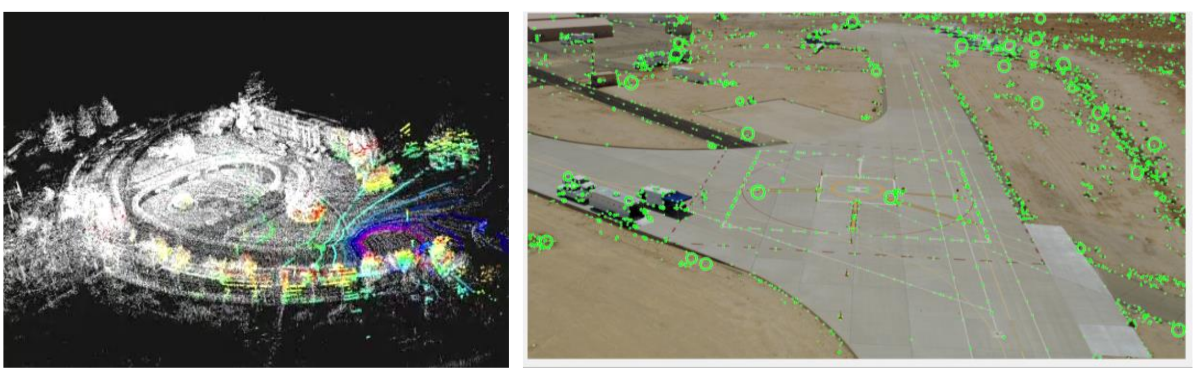

Figure 17. Precision Navigation for Approach and Landing, utilizing onboard lidar (left) and vision (right).

XIV. Hardware Prototypes for Ground and Airborne Sensor Network Experiments

Feasibility analysis for this project includes development of hardware prototypes for subscale flight test experiments. A variety of ground sensor hardware nodes and flight vehicle payload nodes have been developed and fielded, covering radar, visual range imagers, infrared imagers, multispectral sensors, RF ranging, and wireless mesh networking hardware. Figure 18 shows some of the hardware nodes, vehicles, and avionics developed for this project. Details of the flight test experiments and hardware can be found in [42] and [43].

Figure 18. Hardware Prototypes on ground and on vehicle developed for flight test evaluations.

XV. Sub-Scale Flight Test Experiments

In addition to simulation experiments, a variety of scenarios were evaluated using the software and hardware prototypes described above. Overviews of some of the subscale flight scenarios are shown in Figure 19 and in Figure 20, with varying ranges, sensor densities, and placement. Details of these experiments can be found in [37], [44] and [45]. Results from these experiments on the various research topics under investigation in this project have been presented in the references above. Additional flight test data sets have been collected and have been made available to the general research community, as described in [46] and [47].

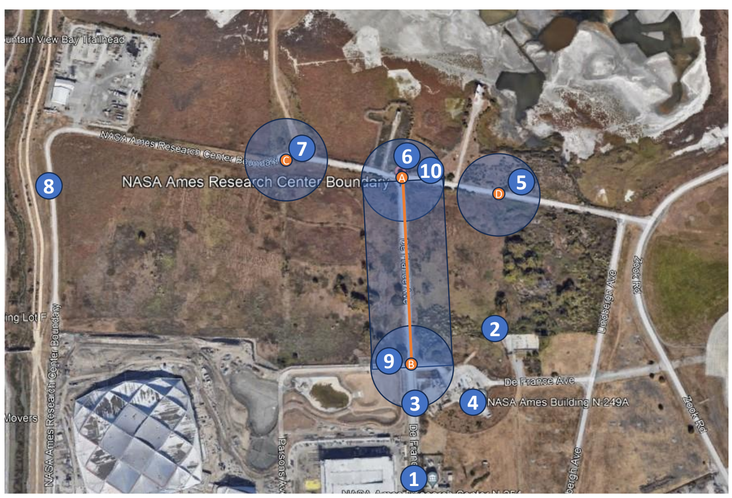

Figure 19. Configurations for Sub-scale Short-Range Flight Test Experiments

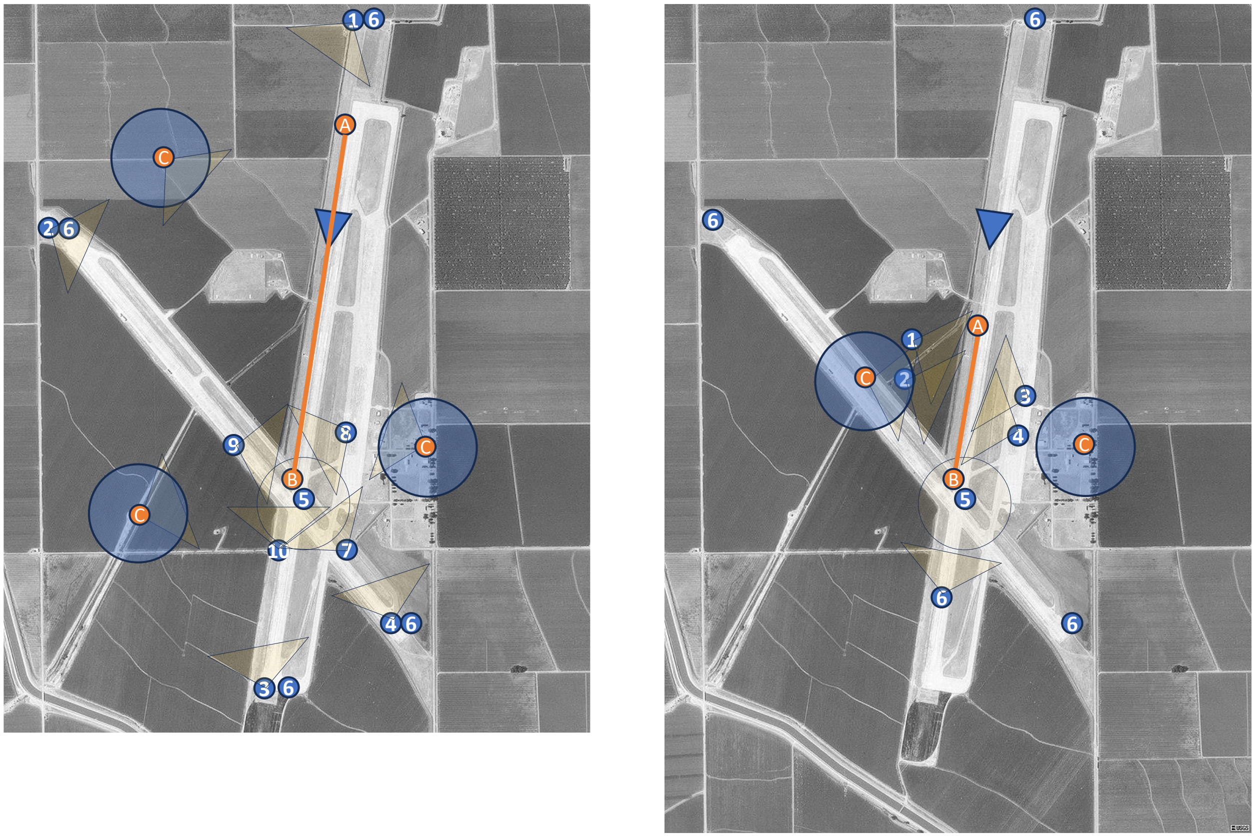

Figure 20. Configurations for Sub-scale Long-Range Flight Test Experiments

XVI. Conclusion

The convergence of urban air mobility with smart space concepts holds promise for addressing many of the barriers inherent in realization of advanced urban air mobility. This paper has presented an overview and summary of distributed sensing research at NASA, which is investigating a smart spaces approach towards meeting these challenges for future urban airspaces. This paper presented a programmatic overview of this effort, summarizing key characteristics, assumptions, and identified needs in the preliminary design study. An overview of current research efforts was presented, summarizing research efforts and preliminary results towards these objectives.

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