Concepts for Distributed Sensing and Collaborative Airspace Autonomy in Advanced Urban Air Mobility

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Emerging concepts for advanced urban air mobility envision responsive air transportation capabilities that will safely move people and cargo in locations presently underserved by aviation. Expanding aviation services to these locales, particularly for high-density autonomous flight operations over urban centers, will require advances beyond the state-of-the-art techniques for airborne sensing. The emerging field of distributed sensing and 'smart spaces' – where sensing, processing, communication, and actuation are embedded in the environment in which agents are acting – may provide attractive alternatives over traditional aviation solutions. This paper outlines the challenges and opportunities for distributed sensing and smart space concepts to meet the emerging needs of advanced urban operations in the national airspace. We present an overview of distributed sensing concepts and research currently being investigated under this endeavor.

I. Introduction

The NASA's vision for Advanced Air Mobility (AAM) is to help emerging aviation markets safely develop an air transportation system capable of transporting people and cargo between locations - local, regional, intraregional, and urban - previously not served or underserved by aviation using revolutionary new aircraft technologies that are only now becoming possible [1]. AAM encompasses a range of innovative aviation technologies - including small drones, electric aircraft, and advanced air traffic management concepts - that may potentially transform aviation's role in everyday life. NASA's AAM efforts include Urban Air Mobility (UAM), the concept of expanding transportation

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networks towards short flight segments that can move people and goods around metropolitan areas at high volume and operating frequency. UAM envisages a future in which advanced technologies and new operational procedures enable practical, cost-effective air travel as an alternative mode of transportation in metropolitan areas. Successful development of aviation as a new urban transportation modality promises substantial benefit to industries and the public in the United States and throughout the world. New technologies and business models are driving these transformational applications of aviation [2] (see Figure 1). UAM concepts have the potential to revolutionize urban transportation and may also play an integral role in the future evolution of smart cities. Smart city initiatives are an emerging concept driven by advancements of information and communication technologies. Smart cities are often envisioned as massive constellations of diverse embedded and mobile technologies distributed throughout the urban environment and connected in real-time across multiple communication networks. Smart city infrastructure is capable of providing continuous data, analysis, and automation services to support vital urban functions in a variety of applications. Many diverse applications have been proposed, including: more-efficient automated control of urban transportation infrastructure resources through monitoring and modeling of the movement of people and materials throughout the city throughout the day; advanced automotive traffic networks supported by smart road infrastructure coordinating with smart vehicle technologies that can provide greater performance, higher throughput, and improved safety compared to current road network systems; smart buildings that monitor environmental changes throughout the system through large networks of distributed sensors that can continually adapt to the needs and comfort of individual occupants with greater control responsiveness, improved building-wide performance, and improved power efficiency as compared to today's building systems; and continuous monitoring of city operations to improve efficiency, equity, and quality of life for citizens in real time [3][4]. Smart space concepts are transforming industries across multiple technology sectors. From wearable personal devices to smart homes, smart vehicles, smart roads, smart buildings, and smart cities - smart space concepts have generated tremendous interest and industry investment in the past few years, and smart technologies are becoming ubiquitous in our everyday lives.

Figure 1. Artist rendition of an advanced urban air mobility system.

Urban mobility concepts with highly automated aircraft providing high volume commercial transportation services to the public over densely populated cities represents one of the most exciting and complex AAM initiatives that faces many challenges [5]. Towards realization of UAM concepts, NASA has developed the UAM Maturity Level (UML) framework, shown in Figure 2, which categorizes anticipated evolutionary stages of a UAM transportation system into six levels. Each UML represents a level of maturity of the UAM ecosystem, with UML-6 representing the ubiquitous integration of UAM into daily life. Each UML is characterized in terms of operational density, complexity, and reliance on automation [6].

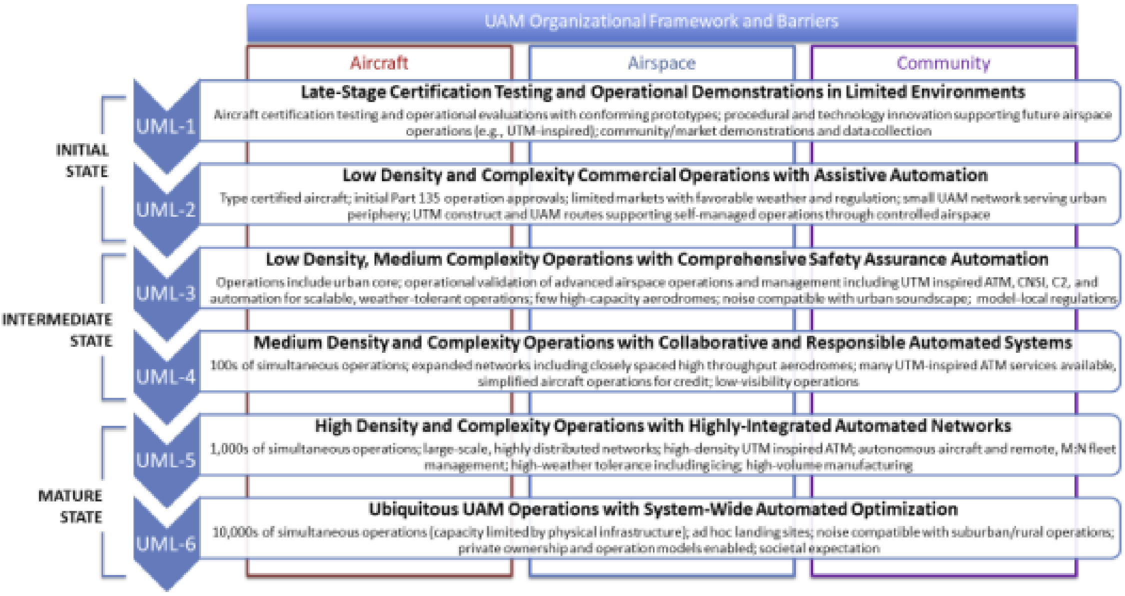


Figure 2. NASA’s UAM Maturity Levels (UMLs) Description.

Achieving the goals for NASA’s UAM vision described in Figure 2 will require significant advancement of techniques and technologies used in aviation compared to today’s state of the art to overcome the barriers and challenges associated with enabling autonomous flight operations over densely populated urban environments. Several critical technologies that are fundamental to the safe operation of today’s national air transportation system were not designed for the unique challenges imposed by the urban environment and UAM; these technologies will not function or will suffer degradations when applied to the UAM domain. Some of the characteristics expected in the UAM environment supporting later UML stages of maturity include:

- Ubiquitous system-wide autonomy and fully-autonomous aircraft operations - As pilots are removed from the aircraft and functional control is transitioned to onboard autonomy and ground operators, the main function of human operators will transition towards managing and supervising functions across multiple aircraft. The onboard pilot’s control functions and situational awareness must be replaced by equivalent technologies.
- High-density heterogeneous flight operations – Urban spaces are defined by high population density and are characterized by high volume transportation needs, currently filled by automotive roadway networks, pedestrian-focused infrastructure such as sidewalks and crosswalks, and various mass transit services which vary between urban centers - such as bus services, light-rail systems, and waterborne transportations networks such as ferry boat services. UAM will require high volume flight operations that are capable of producing compelling aviation transportation alternatives to meet mass-transit needs of future cities.
- Many operators will be utilizing the same airspace with different vehicle types – A major challenge for any transportation system is the efficient utilization of shared resources and development of rules that allow heterogeneous networks of vehicles to interoperate in a manner that is effective, efficient, and safe.
- Degraded and denied Global Positioning System (GPS) performance – GPS is insufficient to meet requirements for positioning in the current National Airspace System (NAS), requiring for instance augmentation through installation of specialized equipment both on the ground and on the aircraft. Introduction of aviation to the urban environment produces additional challenges. Urban canyons are notoriously challenging for GPS and will further degrade or deny airborne GPS. Satellite-based navigation relies on reception of low-power radio frequency (RF) signals, clear RF line of site from receivers to the

satellites, and an environment that provides low RF interference with minimal disturbance, such as caused by RF signal reflections – all of which are challenged for UAM operations within the urban setting.

- Mixture of cooperating and non-cooperative aircraft – The future UAM concepts envision a mixture of cooperative and non-cooperative aircraft sharing a congested airspace. Not all air traffic will be broadcasting their location and trajectory, either intentionally or unintentionally. The wide variety of aircraft, from small UAS to air taxis to cargo transports, will make detection of aircraft difficult. Further, aircraft are not envisioned to be under control of a single controlling entity; rather, each vehicle may likely be under the control of differing entities with differing needs and objectives. Such issues as detect-and-avoid (DAA) and right-of-way rules will need to be addressed.
- Challenging operating conditions in tightly constrained spaces - Urban air vehicles will need to autonomously land with high precision, accuracy, and reliability in all weather conditions, such as in visual meteorological conditions (VMC) and instrument meteorological conditions (IMC).
- Challenging micro-weather conditions - Weather conditions over an urban environment are notoriously complex, difficult to monitor, and difficult to predict. Small-scale and temporary fluctuating wind patterns are expected, exacerbated by interaction of the low-speed air flow around urban structures. As is experienced by current-day helicopter operators, micro-weather conditions in urban environments have the potential to cause issues with AAM aircraft. Such issues include controllability, destabilization, poor ride quality, flight crew and passenger injuries, higher rates of airframe fatigue, and higher rates of vibration/turbulence induced aircraft system failures.
- High-tempo high-volume airspace operations – Operations in the urban environment, such as operations in to and out of vertiports, are anticipated to reach high throughput in later UML stages, increasing the need to develop high precision navigation, control, and detect and avoid technologies that can support dense operations in highly constrained spaces.

II. Distributed Sensing and Smart Airspace Concepts

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 [7][8][9]. 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. 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].

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. (See Figure 3). 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.

Figure 3. Artist rendition of interconnectivity of AAM vehicles within a smart space environment.

The convergence of AAM with smart space concepts may address many of the barriers and challenges for future aviation in a manner that provide significant advantages over alternative and legacy methods. Specific comparative analysis would need to be established for alternative potential candidate solutions with details on a case-by-case basis. However, general advantages that would be expected from a distributed smart space approach would include:

- Better performance – For instance, a distributed positioning system from a large network of distributed sensors can provide better performance, higher reliability, and greater accuracy compared to a GPS-based system in low-altitude flight over an urban environment.
- Higher precision and accuracy – A large set of distributed sensors providing multiple viewing angles of a target can provide greater accuracy and precision compared to a single sensor fixed to one location.
- Enhanced ability to ensure safety and health of the system – Transitioning away from single-sensor sources allows opportunities for cross-validation and health management beyond what is available in today’s aviation systems. Utilization of overlapping observation information across a distributed large-scale sensor network provides the ability for independent validation and continual health monitoring. Cross-validation and monitoring of the health and status of each sensor can provide and greater robustness against sensor/subsystem failures.
- Better protection against unintentional or intentional degradations and attacks (including malicious cyber-attacks, sensor drop-outs, etc.) - Intentional attacks, for instance by sending false information from a malicious service provider or sensor source, can be identified and mitigated through a method of real-time analysis and cross-validation of overlapping sensor observations, providing independent estimates of trust and verification to enhance integrity and security of the overall system. A smart space approach facilitates identification of unreliable or malicious information sources and actors.

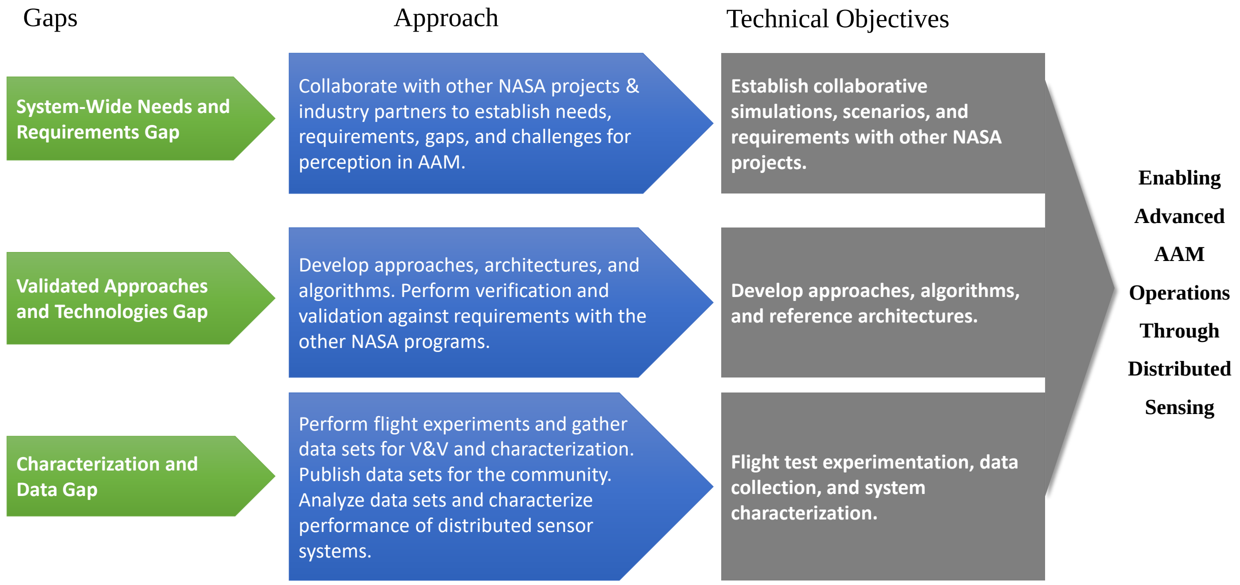
- Greater ability to identify and respond to failures and degradations – Many current aviation systems rely on redundancies to afford protection from individual component failures. However, redundancy cannot address many systemic failures or degradations expected from advanced aircraft systems. For instance, a localized cloud bank may obscure observations of a vertiport from onboard visual sensors trying to detect a landing zone. Switching to a redundant backup sensor on the aircraft will not address this form of failure. However, utilization of a large network of geographically distributed sensors, and developing a distributed sensing framework that can constantly adapt to favor sensors that have clear unobstructed views of the target system, provides a system that is much more robust to a wider class of failures.
- Reduction of cost, size, weight, and power (SWaP) for onboard aircraft subsystems and avionics – Developing and certifying avionics that meet the stringent requirements for manned aircraft operations is an expensive process that is time and resource intensive. The size, weight, and power consumed by certified avionics results in an undesirable reduction of aircraft performance margins. Through a distributed sensing approach, alternative methods of achieving required functions can be provided to the aircraft, replacing onboard avionics with off-aircraft analysis services and virtual avionics that do not require the SWaP consumed by components physically installed onboard the aircraft.

The Distributed Sensing project seeks to address challenges for airborne perception in advanced AAM concepts through utilization of concepts of smart spaces, using distributed observations and information sources in real-time to achieve critical aircraft and airspace operations, and moving away from co-located sensing and control systems approaches. General goals for this project include:

- Identify specific AAM challenges and barriers that can benefit from distributed sensing and smart spaces concepts
- Investigate feasibility of replacing onboard avionics with distributed sensing concepts to achieve critical aircraft functions that are difficult for AAM and UAM in the current state of the art
- Develop framework for incorporating geographically distributed (non co-located) sensors and remote observations of opportunity
- Address sensor drop-outs and degradations (known and unexpected)
- Provide continuous persistent estimates of target systems across multiple overlapping partial observations that meet minimum quality requirements
- Provide continuous evaluation of quality from each observation source (cross-validation and confidence)
- Provide continuous monitoring and automated resolution of intentional disruptions of the airspace, including cyberattacks and spoofing attacks. Cross-validation of information allows for identification of misinformation flowing through the network, and topological restructuring can isolate misinformation and route information away from the affected nodes.

A. Gaps, Approach, and Technical Objectives

As the concept of operations for AAM and UAM are being developed, the evaluation of needs, gaps and barriers towards realization of these concepts must continually be evaluated. This presents a programmatic challenge to the endeavor of research on smart systems for these applications, as high-level requirements are still evolving. The Distributed Sensing project team is taking the following approach, outlined in Figure 4, towards systems-level analysis of this domain. This team has identified three major gaps in the current state of the art that are prohibiting the immediate adoption of distributed sensing concepts. First, a system-wide analysis and requirements gap exists due to the evolving nature of the operating concepts. High-level concepts both drive and are driven-by the technologies that exist at high enough levels of maturity to ensure realistic and feasible concepts. Given the relatively low-level of maturity of smart concepts, current AAM concept of operations do not incorporate many elements of a Smart City/Smart Vehicle/Smart Environment concept. To address this gap, this team is working with other NASA teams and organization who are developing concepts for AAM and adjusting these concepts to utilize smart systems infrastructure. Secondly, a technologies gap exists in that there is a lack of commercial off-the-shelf (COTS) technologies currently available to implement an aviation-grade smart infrastructure service. While potential research technologies have been developed for related fields, such as in the emerging smart automotive industry, the techniques and technologies currently available are typically not directly applicable towards aviation, are non-trivially extended toward aviation needs, or do not meet manned aviation's stringent requirements for safety, performance, and reliability. The Distributed Sensing project seeks to develop techniques and prototype technologies needed to support utilization in support of AAM. Thirdly, a data gap exists in evaluation of the smart AAM concepts. Since AAM concepts are still emerging, there is lack of supporting data to help definitively evaluate the utility of smart solutions concepts in support of future AAM and UAM applications.



Collaborate with other NASA projects & industry partners to establish needs, requirements, gaps, and challenges for perception in AAM.

Develop approaches, architectures, and algorithms. Perform verification and validation against requirements with the other NASA programs.

Perform flight experiments and gather data sets for V&V and characterization. Publish data sets for the community. Analyze data sets and characterize performance of distributed sensor systems.

Establish collaborative simulations, scenarios, and requirements with other NASA projects.

Develop approaches, algorithms, and reference architectures.

Flight test experimentation, data collection, and system characterization.

Figure 4. Distributed Sensing Programmatic Approach

B. Challenges in the State of the Art

In coordination with other NASA AAM project teams, the Distributed Sensing team has identified a preliminary set of gaps have arisen in this preliminary analysis phase based on limitations of today's aviation technologies and their inability to be applied to support high-density urban operations as envisioned under UAM at advanced UML levels. The following presents this preliminary list of challenges.

1. *Scaling Challenges of Current Aviation Technologies.*

Advanced UAM concepts require more stringent requirements for aviation systems than operations over the current airspace system demands, due in a large part to scaling issues with reduced dimensionality and increased density. Many technologies were designed to support nautical mile separation distances between aircraft with flight altitudes above 30,000 feet and on routes on the order of 1,000 nautical miles in length. Advanced UML concepts envision a significant increase in the number of aircraft while the dimensional scale of the entire airspace shrinks to the tightly constrained space of the urban setting that may only be a few nautical miles in size. Higher aircraft operating densities will need inter-vehicle separation distances reduced to 10's-100's of meters between vehicles and other urban hazards - such as buildings, structures, and micro-weather hazards - and will involve a more diverse mixture of varying aircraft classes, including manned and unmanned. Further, the onboard size, weight, and power available on emerging AAM-class aircraft are often orders of magnitude smaller than commercial transport class aircraft. Throughput and tempo of operations is likewise expected to see an order of magnitude or greater increase. Many aviation system technologies - such as ADB-S - would be inundated in scale of advanced UAM. Many critical avionics technologies supporting aviation in the current state-of-the-art and in legacy systems are insufficient. There are currently no clear solutions on replacement technologies, as there are no comprehensive UAM airspace requirements yet developed, and there are no certification paths yet established for AAM vehicle subsystem technologies supporting advanced UML concepts.

2. GPS Reliance Challenges

The increasing reliance on GPS in aviation technologies is leading towards GPS becoming a single-source of failure in many aviation systems [11]. Identifying alternative methods for airborne PNT continues to be a priority for the Federal Aviation Administration (FAA) for the national airspace system. The legacy system of ground-based navigation aids is based on a routing structure that is detrimental to the growth in demand for future NAS operations [12], and cannot be scaled to meet UAM or AAM demands. As an alternative, GPS-derived Position, Navigation, and Timing (PNT) has been a critical enabling technology for the FAA-led NextGen aviation modernization initiative. GPS enables performance-based navigation (PBN) and Automatic Dependent Surveillance Broadcast (ADS-B) services that in turn enable Trajectory-Based Operations (TBO), Area Navigation (RNAV), and Required Navigation Performance (RNP). However, in the case of GPS degradation or denial, aircraft operations will fall back to utilizing legacy navigation systems. This fallback to legacy navigation systems during GPS interference events will degrade performance of the national airspace system to pre-NextGen levels, as critical NextGen improvements, such as RNAV, RNP, and TBO, will no longer function [12]. The expansion of air transportation to urban environments exacerbates the need for GPS-free alternative methods for airborne positioning. Low-altitude aircraft operations above densely populated urban centers poses one of the most challenging environments for GPS-derived positioning. The characteristics of the urban environment, including the presence of large metallic structures in the urban canyons, cause a number of issues, including loss of line-of-site, increased noise and interference, and issues such as signal reflections can return inaccurate positioning information and degrade the resulting navigation solution. Modern aviation systems and services reliant on GPS will not function in a GPS-degraded or GPS-denied environment.

GPS-based aviation systems, such as those providing surveillance and navigation, are inappropriate for the urban environments. GPS dependent legacy aviation systems and services, such as self-reported ADS-B surveillance and Ground-Based Augmentation Systems (GBAS) supporting precision approach and landing at qualified airports, may not be appropriate for UAM applications.

3. Challenges with the Urban Environment

Unfortunately, GPS-free solutions for surveillance, navigation, airspace monitoring, and conformance monitoring in the current state of the art, including legacy technologies utilized in the national airspace system, are often likewise difficult to apply to urban UAM scenarios due to the characteristics of the urban environment. The urban environment features large metallic structures that are densely spaced, can obscure line-of-site, and can cause significant interference with EM/RF based technologies, specifically those that were designed for high-altitude, clear line-of-site operating conditions, or the expectation of minimal ground clutter. Additionally, the EM/RF environment in the urban setting is being increasingly utilized due to growing utilization of wireless technologies over a wide number of applications, from city-wide services to personal home devices, which increases the possibility for EM/RF interference from neighboring RF wavelength bands.

Independent surveillance utilizing ground-based radar systems is a traditional method used in the current airspace system. Unfortunately, ground-based radar is notoriously difficult to use for surveillance of low-altitude urban flight due to characteristics of the urban setting. The urban landscape introduces significant ground clutter noise and signal reflection for radar, and building structures create non-line of sight scenarios shadowing radar and other communications signals [13][14][15]. Developing a network of distributed low-powered ground radar systems to provide surveillance may be a potential solution, but fundamental issues such as interference between radar transmissions, rejection of noise and reflections due to ground clutter, low-power radiation safety considerations, life-cycle operating costs, and interference issues must be addressed before such networks can be realized [16]. Independent surveillance through distributed networks of heterogenous sensors covering multiple sensor modalities, as envisioned in the Distributed Sensing project, may provide an attractive low-cost alternative.

Precision enroute navigation and automated precision approach and landing (PAL) is also problematic for AAM in the UAM context. Beyond modern GPS-based navigation methods, legacy solutions such as the Instrumented Landing Systems (ILS) will be difficult to apply to support the UAM concept of operations. ILS landing systems are a short-range RF-based system composed of two directional radio signals, a localizer transmitter for direction navigation, and glideslope transmitter for vertical guidance. This RF system is difficult to install in the urban setting due to interference from the urban landscape. As such, ILS systems are unable to support approach and landing for helicopters and urban-area heliports in the current airspace system. Further, no approved criteria or process exists to define development of such an instrument flight rules (IFR) approach that can be certified for use in heliports or vertiports [17]. Further, the current network of ground-based navigation aids (NAVAIDS) - such as Very High Frequency (VHF) Omnidirectional Range (VOR) and Distance Measuring Equipment (DME) stations - used to support navigation in the national airspace system are also difficult to apply for UAM. These RF-based systems face the same difficulties as other RF navigation systems in this environment, and the NAVAID system is difficult to scale in a cost-effective manner to support UAM operations [12].

C. Potential Applications for Distributed Sensing

AAM needs that can be supported by smart system concepts can be categorized into the following technology focus areas and applications:

- Alternative Positioning, Navigation, and Timing (APNT), e.g., supporting Precision Navigation and Precision Flight Control
- Airborne Detection, Tracking, and Estimation, e.g., supporting Detect and Avoid, Vertiport Airspace Monitoring, and Corridor Surveillance
- Weather and Atmospheric Sensing for Weather Tolerant Operations
- Health Monitoring, Prognostics and Diagnostics
- Distributed Environmental Hazard Sensing

Several scenarios are currently being investigated supporting this research These use cases highlight the challenges due to limitations of current technologies and techniques to support UAM and AAM operational concepts.

- Corridor Surveillance
- Vertiport Airspace and Conformance Monitoring
- Precision Approach and Landing
- Hazard Sensing and Avoidance – Environment Hazards, Air/Weather Hazards, Ground Hazards

These scenarios are discussed in the research section below and in the associated references.

D. Key Characteristics and Assumptions for Distributed Sensing

The following are key characteristics and assumptions for smart spaces and distributed sensing research operating in a future AAM aviation system context. These key characteristics include:

- Topologically Dynamic
- Geographic Mobility in Data and Processing
- Collaborative and Market Incentivized
- Overlapping Sensors with Partial Observations of Varying Quality
- Smart Airspace Composed of Interoperating Smart Elements (e.g., smart aircraft, sensors, and services)
- Complex Communication Constraints (e.g., time varying latency, bandwidth, and quality of service)
- Complex Time-Varying Large-Scale System (dynamic and difficult to predict)

These characteristics will be elaborated in the motivating problem discussion below.

III.Motivating Scenario

Consider the following motivating problem illustrated in Figure 5. Consider a vehicle, V1, traversing a smart space enabled environment along the flight path shown. Consider of set of heterogenous sensors, S1 to S5, operating within the space, some of which are fixed, some of which are non-stationary. In the illustration, sensor S5 is attached to vehicle V2 that is moving along its own flight path. Consider each sensor provides two angular measurements, azimuth, and elevation, of target vehicles within the sensor's associated sensor volume. Assume sensor estimation accuracy is a function of distance and assume there is uncertainty associated estimates that is specific to each sensor. Assume all elements in the environment (vehicles, sensors, observers) are cooperative 'smart' systems; assume all elements have the ability to communicate with each wirelessly, and assume each element has some computational capability to host algorithms. Assume an underlying wireless communication network that is subject to communication constraints - such as bandwidth limitations, latency, and jitter – that prevents all information from being shared with everyone at the same time. The communication constraints are assumed to be time-varying as a function of the information path and the current state of the system. Assume there are sensors onboard V1 capable of reporting rotation rates and linear acceleration. Assume vehicle V2 has full knowledge of its state, and assume all elements in this scenario are cooperative, in that information can be accessed in real-time by vehicle V1. Consider a stationary observer, M, responsible for monitoring the airspace.

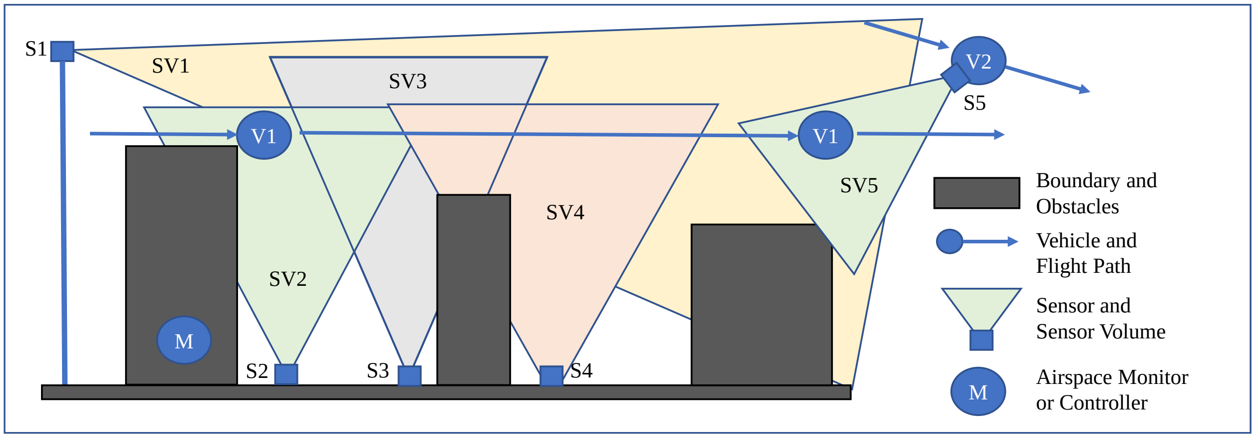


Figure 5. Simplified Motivating Problem

We pose a set of illustrative problems associated with this motivating scenario: (1) (Independent Surveillance) Provide continuous and persistent estimates of the state of aircraft operating within the airspace to a monitoring observer, with estimates that are independent of the sensors onboard the estimated aircraft, sufficient for surveillance (i.e., lower rate and precision required relative to the navigation problem); (2) (Precision Navigation) Provide a continuous and persistent estimate of the full state of vehicle V1 to the vehicle sufficient for closed-loop flight control that may utilize sensors onboard V1 (i.e., higher rate and precision that surveillance, includes velocity estimates); (3) (Sensor Health Cross-Validation) Provide continuous evaluation of the health and accuracy of sensors S1 through S5 while the vehicle is in operation.

This simple motivating scenario highlights several properties of distributed sensing problems within a smart space construct that are relevant to AAM applications. If the position of the sensors are given ahead of time to the vehicle as a priori knowledge, this information can be used during planning and execution to control the aircraft to have sufficient observability throughout the traverse. However, we are limiting the scope of this problem to distributed estimation only, so we assume the vehicle is entering a previously unknown environment with unknown sensor locations and traversing along a pre-planned fixed flight path. Challenges arising in the motivating scenario of interest to Distributed Sensing are described in the following sections.

1. *Topologically Dynamic Problem Space*

Distributed sensing in a smart space context to support UAM operations will require a system that can dynamically restructure to take advantage of sensing opportunities that present themselves at any given time while satisfying complex constraints on the shared resources of the space. We assume the airspace will be shared by multiple self-interested entities, and we assume the complexity of the problem prohibits relying on pre-determine flight paths and estimation networks. Solutions will require topological diversity in the structure of information flow. For instance, consider two time instances as illustrated in Figure 6. At the time t_a shown Figure 6 (a), vehicle V1 is within the sensor volumes of S1, S2, and S3. Information from these sensors can be utilized in an estimation network to estimate the position of V1. This requires a real-time stream of information to flow through certain nodes in the network. In (a), information must flow from S1, S2, and S3 into an estimation network, and the output of this estimate must flow to the observer M as the information consumer. At another point in time t_b, shown in Figure 6 (b), the vehicle is no longer in view of sensors S1 through S3, but is in view of S4 and a vehicle mounted sensor S5 on vehicle V2. Estimation of the state of V1 will requiring information from V2 to rectify the sensor readings from S5. The information topology must route information from S4, S5, and V2, into an estimation network B, then route this resulting estimate to the information consumer. The topology determination problem involves determining an acceptable topology that meets the requirements and constraints of the problem.

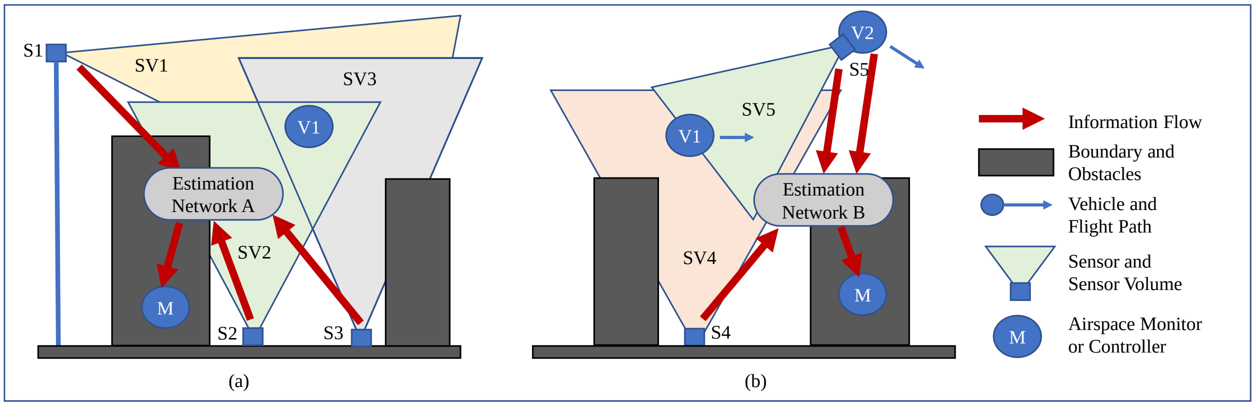


Figure 6. Topologically Dynamic Estimation Structures

2. *Geographic Mobility in Data and Processing (Edge Computing)*

Consider the two topological time instances shown in Figure 6. The estimation networks A and B are algorithmic elements that needs to be hosted on one of the computational nodes in this system. The service migration problem consists of determining the assignment of these algorithms on one or more processing elements in the environment such that all constraints - including communication and processing load limitations - are satisfied that meets the requirements of the data needed by the consumer [18].

3. *Overlapping Partial Observations with Varying Quality*

At any instance in time, we assume sufficient observability will determined by overlapping sensor observations of varying quality. Remote sensors as illustrated in the motivating scenario typically have performance that is a function of several factors that will be specific to each sensor, assuming operation over a heterogenous mixture of sensors. Estimation accuracy, for instance, is often a function of position of the target within the sensor volume and distance of the target from the sensor. Vision-based estimation and tracking from cameras are a function of the optical properties of the imagers. Radar systems are a function of factors that include the distance to the target and the target's RF cross-sectional area. Preliminary sensor models were presented and discussed in [19]. To provide continuous estimates the meet minimum performance requirements, these networks will need to take advantage of several sensors that provide temporary partial observations of the targets being tracked.

4. *Collaborative and Market Incentivized*

The development of an incentivized market that encourages aviation services to support a collaborative smart airspace concept is necessary but beyond the scope of the research described in this paper. Several associated research efforts are currently underway to establish such financially incentivized markets that will encourages vehicle manufactures, operators, and service providers to take part in such an ecosystem. Such efforts include the Unmanned Traffic Management (UTM) project [20] and the Data and Reasoning Fabric (DRF) project [21].

5. *Smart Airspace Composed of Interoperating Smart Elements (Vehicles, Sensors, Services, etc.)*

This research investigates the benefits derived from the convergence of smart space concepts with future AAM air transportation systems. A smart airspace in this context is defined as a large-scale collaborative environment where massive networks of smart elements – such as sensors, actuation, processing, services, vehicles, operators, etc. - are distributed and embedded throughout the environment as shared resources to support the functions and goals of users of the space, and interoperating over a series of overlapping communication networks that allows information to dynamically flow throughout the system as needed at any given time. All elements of a smart space must be 'smart' in that they can interact with other elements throughout the space, which requires a certain level of minimum equipage (e.g., hardware, including a communication system, and software).

6. *Complex Communication Constraints*

Airborne wireless communication networks have received much recent attention in both industry and academia. These networks are characterized by frequently changing network topologies, vulnerable communication connections, complex interference issues, and a widely time-varying quality of service that is difficult to predict [22]. Information flow over these networks is expected to suffer from bandwidth constraints, varying time latencies, intermittent dropouts, and time-varying performance.

7. Complex Time-Varying Large-Scale System (dynamic and difficult to predict)

The airspace and resulting estimation problems are expected to be complex, time-varying, and uncertain. The AAM airspace will be shared by many self-interested entities independently operating a wide range of varying aircraft types (from small drones to helicopters and autonomously operating air taxis) with high throughput. The complexity of the problem prohibits relying on pre-coordinated pre-determined operation plans that have been accepted by all users of the airspace a priori which would allow resources to be pre-allocated and estimation networks structures to be predetermined.

IV. Distributed Sensing Research and Applications

The following sections presents a roadmap that outlines the major topic areas currently being investigated under the Distributed Sensing project. These sections provide a general overview of each topic area with a list of publications and references that provide in depth discussion on each topic.

Evaluation and experimentation of this research will be performed using the following four methods:

1. Full-scale AAM Simulations - Medium-Scale Simulation of Regional AAM Operations
    - Middle Harbor Park (MHP) to Fifth and Mission Garage (FMG) route, single vehicle/single flight scenario using NASA’s AAM reference design vehicle models
    - Regional vertiport-to-vertiport operations, including the MHP-FMG route above, up to 100 simultaneous flights using NASA’s AAM reference vehicle model along multiple routes
2. Sub-scale Flight Testing – Vertiport Operations
    - Flight testing at NASA Armstrong Flight Research Center’s full-scale vertiport flight test facility using a small multirotor sUAS as a subscale flight test platform
    - Smart-vertiport hardware mockup/prototype
    - Smart-vehicle prototype avionics installed on the sUAS
3. Sub-scale Flight Testing – Corridor/Enroute Operations
    - Flight testing at NASA Ames Research Center using a small multirotor sUAS as a subscale flight test platform flying at low-altitude
    - Smart-corridor hardware mockup/prototype
    - Smart-vehicle prototype avionics installed on the sUAS
4. Simulation of Sub-scale Flight Test Experiments
    - Hardware-in-the-loop simulation configurations which supports development and testing of hardware used in the sub-scale flight tests above.

A. A Structurally-Adaptive Framework for Distributed Airborne Sensing over Real-time Collaborative Information Sharing Networks

Towards development of a general framework for distributed sensing, the research in [23] 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, presents 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.

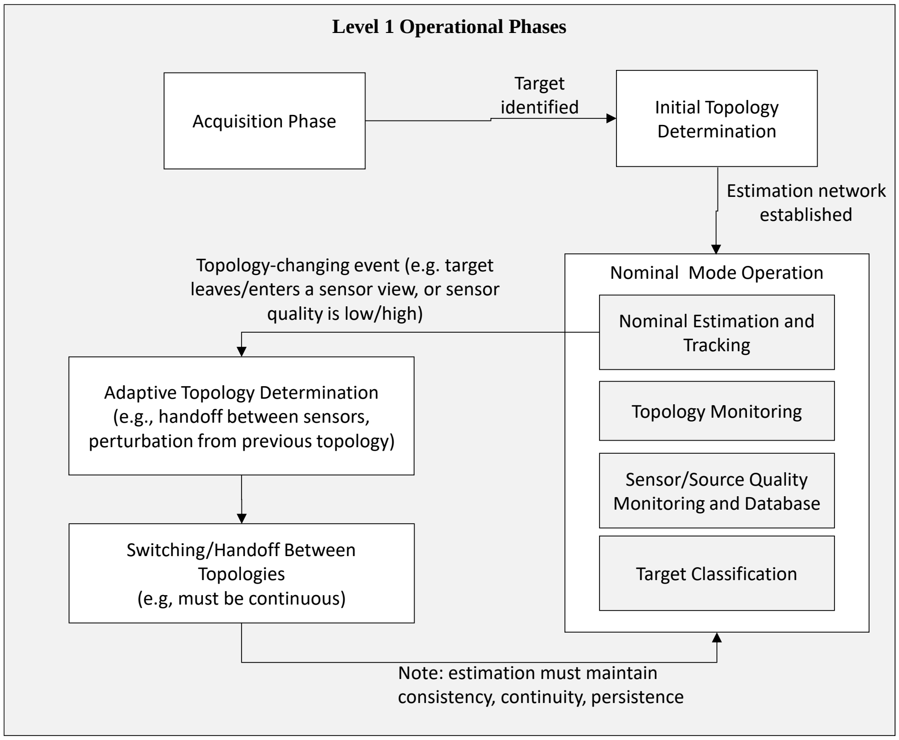


Figure 7. Operational Model for a General Framework for Distributed Sensing

The general operational phases of the framework are show in Figure 7. 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. One 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, 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 sensos 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 7 represent the major 'Level 1' operational modes. Additional details of the framework can be found in [23].

B. Development of an AAM Regional-Operations Simulation Testbed

Evaluation of distributed sensing research will make use of a moderate-scale high-fidelity simulation of AAM flight operations occurring over a regional area. Details of the simulation system are presented in [24]. A simulation infrastructure was developed to simulate flight operations around regions such as the San Francisco-Oakland Bay area at a moderate-scale (tens to hundreds of flights) that incorporates detailed AAM vehicle models and flight controls necessary to support research in distributed sensing and airborne autonomy in general. The simulation utilizes a NASA AAM concept vehicle dynamics model integrated with a custom flight management system and flight control system to simulate all flight phases accurately. The simulation incorporates a detailed simulated urban environment and includes glass cockpit displays to monitor aircraft operations. Simulation models have been integrated to simulate air and ground-based sensors, such as Radar and LiDAR. A commercially available rendering engine (X-Plane 11) is used to simulate vision-based sensors (such as onboard and ground-based cameras) with a detailed graphical model of a city at different times of the day and weather conditions. The referenced paper presents details of the simulation and software architecture used for simulating AAM traffic over this urban region. Renderings of vertiport mockups are shown in Figure 8 and a view from one of the sensors is shown in Figure 9.

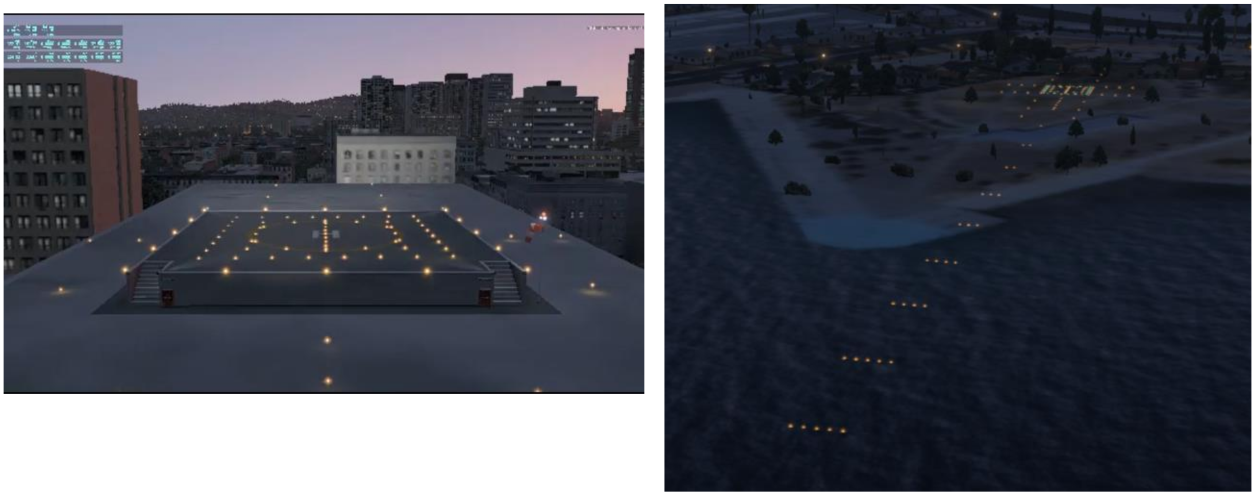


Figure 8. Vertiport Simulation Mockups

Figure 9. Simulation View

C. Precision Navigation and Precision Approach and Landing

AAM concepts of operations require precision navigation to support enroute corridor operations as well as supporting precision maneuvers for approach and landing in urban area vertiports. Currently there are no established methods for providing autonomous navigation and control for vehicles operating in these environments. While many alternative single-sensor methods have been proposed in the literature, these approaches are generally insufficient to meet all requirements, often suffering from debilitating failure modes specific to the characteristics of the sensor. Distribute sensing concepts envisions a future smart airspace where vehicles can rely on real-time estimation from a distributed heterogenous suite of sensors, both onboard the aircraft and embedded in the environment, that can be combined to provide navigation inputs to the flight control system that meet the requirements for performance and reliability. The following research is leading towards meeting the requirements for precision navigation through distributed sensing methods in a smart airspace environment. The initial research focused on developing estimation techniques that utilize multiple onboard sensors for navigation and state estimation. This work is currently being extended to incorporate additional ground-based sensors.

In [25] and [26], the authors present a vision-based Precision Approach and Landing (PAL) system utilizing known landmarked features. The presented system utilizes correspondence methods to establish a baseline navigation system based on reference landing lights installed on a simulated smart vertiport mockup. The landing lights and markings in the vertiport mockup follow guidance from the FAA AC 150/5390-2C. This document specifies heliport design guidelines, and the authors assume this reference is an appropriate reference to use until vertiport-specific guidance is published. A coplanar algorithm determines pose estimation, which feeds into an Extended Kalman filter that combines IMU with vision to create a sensor fusion navigation solution for GPS-denied environments. The state estimate leads to glideslope and localizer error computations, which will be pertinent for designing and deriving guidance laws and control laws for an AAM PAL system. The general system inputs/outputs are shown in Figure 10. The IMU and vision navigation solution presented shows promising simulation results, evaluated in the simulation systems described in section IV-B [24].

In [27], the authors investigate alternative vision-processing methods to support distribute sensing estimates from onboard vision systems that use landmark-free methods. The author utilizes flight test vision data collected over a full-scale vertiport mockup at NASA AFRC, and flight test data collected over NASA Ames that includes vision and LiDAR data sets (Figure 11). The authors compared several ‘pre-canned’ algorithms for Simultaneous Localization and Mapping (SLAM) utilizing two primary onboard sensors: cameras and LiDAR. SLAM techniques provide localization information and precise mapping of the physical environment without prior knowledge of the surroundings. SLAM may play a vital role in aeronautics and aerospace applications, particularly when aircraft must operate in environments where traditional localization services may be degraded or unavailable. The authors compared several ‘pre-canned’ 3D SLAM algorithms in this initial study: ORB-SLAM, ORB-SLAM2, LOAM, A-LOAM, and F-LOAM. The study identifies strengths, weaknesses, and deficiencies in these algorithms from the flight test data. The results from this study are guiding current research efforts that will combine various sensors modalities, both onboard and in the environment, in a manner that can provide consistent and reliable state estimates to meet onboard precision navigational needs for AAM vehicles operating in advanced UML environments.

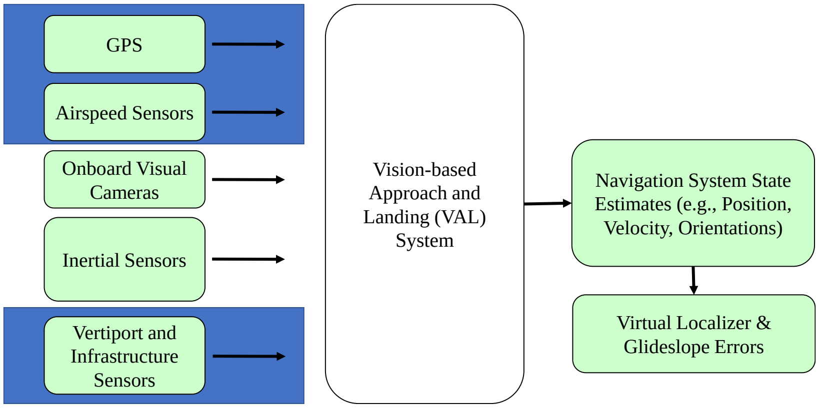


Figure 10. Multi-Sensor Vision-Based Approach and Landing System

Figure 11. sUAS Flight Tests at NASA Ames Research Centers and initial processing results.

D. Distributed Estimation Networks and Filtering

In [28], the authors investigate state estimation of aircraft across a distributed set of ground-based sensors to provide an independent method for surveillance. Autonomous operations are a crucial aspect of Advanced Air Mobility and other emerging aviation markets. In order to enable this autonomy, an accurate and detailed understanding of the positions of the various vehicles in the air is necessary. Full localization independent of onboard sensors makes the system suitable for noncooperative vehicles. This paper focuses on object tracking that relies on distributed ground-based sensor fusion, considering specific properties and limitations of different sensor types. The paper presents results from simulations described in section IV-B [24]. The results show satisfactory performance of the proposed architecture in nominal scenarios with full coverage and observability. Dropouts of individual sensors affect the accuracy of the tracking results, which agrees with expectations for partial coverage when full localization is no longer achievable.

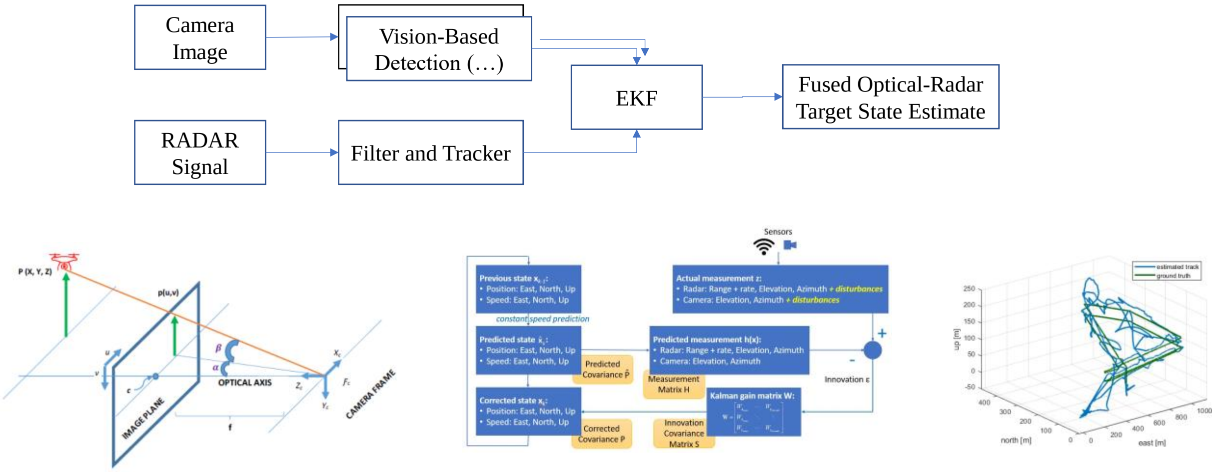


Figure 12. Fused optical-radar aircraft detection and tracking system

In [29], distributed estimation is further investigated with an optimal data migration strategy to address the migration problem, extending the research presented in [18]. The authors present an Extended Kalman Filter based framework for airborne target tracking using dynamic information fusion from multi-modal sensors with geodiversity. First, the algorithm execution location is determined using an optimal data migration strategy. Next, the sensors information is dynamically fused at each estimation instance using validity flag for each sensor reading. In the final step, the target estimation is updated based on the fused innovation vector. The approach is applied to synthetic data generated from the radar and camera models located on the ground for the simulated target flight in simulation environment described in section IV-B [24].

E. Characterization of Sensor Degradation in Fog

In [30], the authors present results from a collaborative effort between NASA and Sandia National Laboratories to characterize sensor degradation in a controlled test-chamber environment. Characterization of sensor degradation in real-world conditions is critical to understanding how to combine multiple sensor modalities in a distributed sensing context, where the architecture can be designed to utilize overlapping sensors data from multiple sources to provide robustness against degradations. Towards these goals, the authors developed a perception testbed at NASA Ames Research Center to collect data from an array of sensing systems representative of those that could be found on a future UAM vehicle. This testbed, featuring a Light-Detection-and-Ranging (LIDAR) instrument, a long-wave infrared sensor, and a visible spectrum camera was deployed for a multiday test campaign in the Fog Chamber at Sandia National Laboratories, in Albuquerque, New Mexico. During the test campaign, fog conditions were repeatedly created for tests with targets including humans, resolution charts, and a small unmanned aerial vehicle (UAV). This paper presents details of the developed perception testbed, the experimental setup in the Fog Chamber, the resulting data, and presents an initial analysis of the data which evaluation of methods to increase contrast through filtering techniques.

F. Subscale Flight Test Experimentation

In [31], results from initial data collection flight tests are presented (Figure 13, Figure 14). The evaluation of distributed sensing concepts will benefit from real-world flight data collected over environments relevant to the application. One potential application is enabling autonomous precision landing of VTOL aircraft that is not reliant on GNSS or legacy navigation infrastructure. Benchmark datasets in this context are scarce in the public literature. This paper introduces a novel dataset containing [N] examples of a VTOL approach and landing scenario, as well as other video and data around the terminal area. The dataset provides camera images with 4K resolution (4096x2160 pixels) at 60 Hz correlated with IMU and other sensors. Images of a grid of April tags as well as overhead, orthographic views of the landing area are included for lens intrinsic calibration. Ground truth for trajectory and pose evaluation is provided by the aircraft's INS-GPS blended navigation solution and the pan, tilt, and roll angles of the camera gimbal joints. Surveyed geographic locations of the touchdown and lift off area (TLOF), final approach and take-off area (FATO), and Safety Area are included for ground truth of visual features in an outdoors environment with bright sunlight. The dataset also includes meteorological conditions, including solar flux, recorded at nearby ground stations. The landing location is the 01H helipad located at the NASA Armstrong Flight Research Center. The helipad markings are consistent with FAA heliport design guidelines. The approach begins 1500 ft (460 m) downrange at an altitude of 250 ft (76 m) above the surface and uses the 238 approach to the landing zone. The full dataset is publicly available including raw and calibrated data. This dataset is the first of several being collected by the team, with future plans to make this data set available to the community.

Figure 13. Flight image captured over the AFRC vertiport facility.

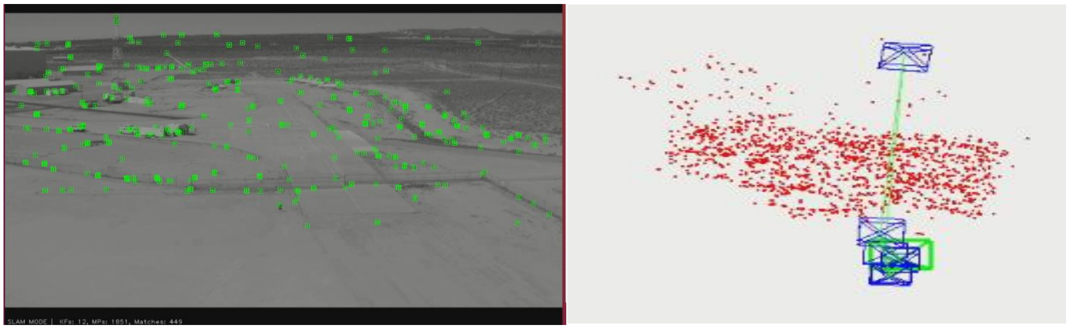


Figure 14. Vision-based approach and landing evaluation from AFRC flight test data.

V. Summary

The convergence of urban air mobility with smart space concepts holds promise towards 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. This paper presented a programmatic overview of this effort, summarizing key characteristics, assumptions, and identifying needs in preliminary AAM designs. Potential applications were presented. A notional scenario was described to help develop the distributed sensing functional requirements, highlighting properties of distributed sensing problems within a smart space construct. A general overview of current research efforts was presented, summarizing preliminary research efforts towards these objectives.

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