Distributed Sensing and Reasoning for Advanced Air Mobility Health Management and Mission Assurance

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As envisioned, Advanced Air Mobility (AAM) and Urban Air Mobility (UAM) will introduce new vehicles and operations within the national airspace, moving people and cargo safely and efficiently at a much larger scale than today. Driven by transformative technology and revolutionary aircraft, this movement must still manage technical, regulatory, operational, and policy challenges. NASA's work in support of AAM and UAM includes, but is not limited to tools, technologies, and architectures for distributed sensing of aircraft, data & reasoning services exchange, Human-Autonomy Teaming (HAT), contingency management, and vehicle health management. This paper builds upon these concepts and evaluates the use of distributed sensing and infrastructure assistance towards health management and mission assurance of UAM vehicles in specific operational scenarios. Through analysis of these example missions, aided by the data produced by the conceptual distributed sensing and reasoning infrastructure, we define opportunities for state estimation, diagnosis, and key decision points affecting the health state of the vehicle and the airspace volume. As a result, we define a number of measurable health state parameters providing relevant information to drive decision-making in contingency situations or feed automation tools in support of operators and managers.

I. Nomenclature

AAM	=	Advanced Air Mobility
ATC	=	Air Traffic Control
$COPs$	=	Cooperative Operating Practices
ETM	=	Upper Class E Traffic Management
HAT	=	Human Autonomy Teaming
VM	=	Vertiport Manager
FM	=	Fleet Manager
$LIDAR$	=	Light Detection and Ranging
PIC	=	Pilot In Control
$IASMS$	=	In-Time Aviation Safety Management System
$RADAR$	=	Radio Detection and Ranging
$RPIC$	=	Remote Pilot In Command
$RPAS$	=	Remotely Piloted Aircraft Systems
FAA	=	Federal Aviation Administration
NAS	=	National Airspace System
UTM	=	Unmanned Aircraft Systems (UAS) Traffic Management

II. Introduction

Advanced Air Mobility (AAM) and Urban Air Mobility (UAM) represent an expansion of the national airspace to include new services and transportation utilizing revolutionary new aircraft and transformative technology [1, 2]. Maintaining a safe and efficient airspace while increasing the number of daily operations and adding new operational paradigms enabled by UAM vehicles will require new levels of automation in support of air traffic controllers, vehicle operators, and passengers[3]. NASA has produced a vision of the technologies required to achieve these desired operational capabilities and the technological maturity level necessary of the UAM air transportation

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system over time; they are defined by UAM Maturity Level (UML) and span an initial state of certification testing and low density operation to a mature state with a high density of complex operations [4]. At each level, the complexity of the operations in the airspace increases as does the overall reliance on automation. Notably, with a large increase in vehicles and operations, additional ground sensing infrastructure would clearly benefit air traffic control efforts. There are opportunities to use this data for vehicle and airspace health management. The work presented in this paper explores those opportunities for health management via distributed sensing within UAM operations.

Analogous to traffic cameras used to monitor highways and interstates, the conceptualized infrastructure of distributed ground sensing systems would support the monitoring of air corridors used by AAM vehicles. In addition to traffic monitoring, such a distributed sensing system could potentially assist in vehicle and airspace health monitoring and ultimately benefit mission assurance. The distributed sensing system is here defined as an interconnected system of sensing nodes used to monitor a region of airspace for aircraft. Such nodes could feature ranged sensing systems like vision, infrared, lidar, radar, ect. and weather monitoring sensors.

A key feature of the distributed sensing system, different from traditional highway traffic cameras, is the proposed highly accessible nature of the nodes, meaning that vehicles may easily connect to and request both data and information products from the infrastructure at any moment during flight operations. The second key difference is the inclusion of compute systems with ground nodes for processing of the collected data, calculation of sensor fusion-based information products, or the processing of assigned compute tasks from vehicles as they pass by. Ground sensing nodes would ideally be placed at regular intervals along flight corridors and surrounding areas where complex operations occur such as vertiports or key intersections of flight corridors. Finally, the interconnected and distributed nature of the system of ground sensing nodes means that they are ideal as data aggregators and could retrieve data from other sources when called upon by aircraft, including data from other sensor nodes.

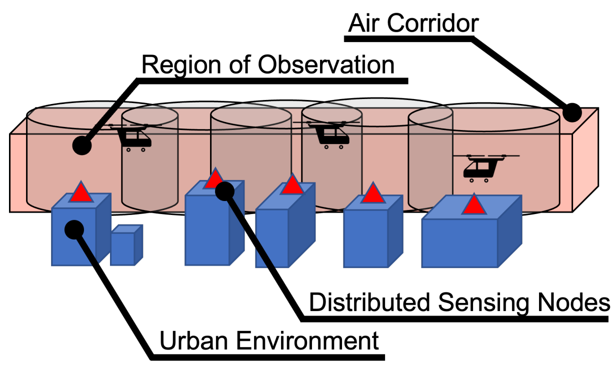

Fig. 1 Concept for distributed sensing along air corridors to support AAM operations.

Literature features many related topics including cases exploring the use of infrastructure to assist autonomous vehicles [5], the development of aviation safety management systems that include services, functions and capabilities (SFC's) which deliver examples of the calculated safety information benefiting UAM mission assurance [6], and examples of what a distributed sensing framework might look like[7]. Previously, Dr. Baidya of U.C. San Diego explored the feasibility of infrastructure assistance to autonomous UAV systems [5]. He evaluated the ability of a communication infrastructure to support the flow of information from the UAV to infrastructure enabling infrastructure-based assistance in the form of remote navigation assistance and compute task offloading. Under this definition of remote navigation assistance, the vehicle would periodically transmit telemetry to the infrastructure or support system, then receive information assisting in de-confliction or guidance on flight corridors. Computing task offloading is also defined as the assigning of complex computing tasks to ground-based computing infrastructure followed by closed-loop control. Offloaded tasks can include precision navigation, using the returned data product from the offloaded task. Each of these infrastructure supported tasks have individual communications requirements and absolute limits on transmission time, and deadlines for processing that must be met to facilitate closed loop control. In this work, Dr. Baidya concluded that multiple communications methods were necessary to meet the varied requirements for the proposed operations supported by infrastructure assistance. In this example, the author considered navigation assistance and computation assistance but precluded vehicle or airspace health management methods that are the topic of this paper.

Separately, a concept of operations for an aviation safety management system for AAM was proposed by NASA researchers from both Langley Research Center and Ames Research Center [6]. This conops addresses the need for safety assurance in AAM operations through an In-Time Aviation Safety Management System (IASMS). This system concept utilizes shared and IASMS-specific services to mitigate risks before they can lead to an incident or accident. Such services target safety risks and provide information critical to detection and mitigation of the emergent behavior. Within this service-oriented architecture, services provide information or data to a user or operator who subscribes to that service. These services use data from the vehicle as well as data from infrastructure to quickly manage known risks, discover unknown risks, and inform operators responsible for decision-making. Service examples include a detect and avoid safety monitor, vehicle health monitor, GPS degradation models, and advanced weather models. This extensible safety management system leverages disparate data sources, including vehicle telemetry provided though subscription to services, and provides an excellent example of how the proposed health management and mission assurance methods described in this paper may be delivered to operators and managers.

Finally, a structurally-adaptive framework for a distributed airborne sensing system, presented in previous work, provides a conceptual and mathematical formulation of an infrastructure network supporting AAM operations including GPS-free navigation such as enroute and terminal-vicinity operations and surveillance and conformance monitoring of aircraft in airspace corridors [7]. The proposed distributed sensing framework incorporates sensors and resources geographically distributed throughout the airspace and outlines local and global operational phases for adapting the network topology to achieve a specific sensing goal. Once the network topology is set, the network collects data, processes the data, and produces information products for the consumer. While this framework is presented in the context of enabling precision navigation and supporting surveillance, such capabilities have direct applicability to health management of both the vehicle and airspace as will be investigated in this paper.

Given the supporting literature, it is clear that there is great interest in the area of infrastructure assistance for health management in AAM operations. In this paper, we present a preliminary investigation of distributed sensing and reasoning for advanced air mobility health management and mission assurance. This work is focused on the following research questions:

1) *When can distributed sensing and infrastructure assistance increase the safety of AAM operations?*
2) *What information products produced by distributed sensing and reasoning would benefit health management and mission assurance?*

To support this investigation and address these research questions, we pose a set of motivating scenarios to explore the interaction between vehicles and the sensing and reasoning infrastructure, highlight benefits to vehicle and airspace state awareness, and analyze the decisions that result from this knowledge. This paper is structured as follows: the approach for distributed sensing and reasoning is next outlined, followed by the case studies and individual scenarios, before concluding with a discussion of the impacts to decision-making and automation tools. The paper ends with a conclusion summarizing results and listing next steps for the research.

III. Approach

Within general aviation it is not uncommon for pilots to call on ground-based air traffic controllers to request supporting information such as weather conditions including winds, information regarding landing sequence, tracking information including ground speed, altitude, current heading, heading to fly, position & distance from/to a location, and chart information. The proposed approach for distributed sensing and reasoning for advance air mobility health management and mission assurance builds on this concept by increasing the number of tracking systems with the introduction of a distributed sensing infrastructure of ground nodes. Additionally, it automates the methods for requesting support information; and finally broadens the capabilities of the interaction to include health management information products and airspace volume health management alerts for vehicles on approach. Although the physical infrastructure and vehicle operations targeted in this approach are years away from reality, exploration of this notional system defines clear benefits for safety and mission assurance in nominal UAM operations as well as during contingency events. Furthermore, these benefits also support decision making by both vehicle operators and managers of airspace volumes, including vertiport managers. At a minimum, the notional distributed sensing infrastructure along flight corridors increases overall state awareness and as will be shown, may also provide health management information products vital for decision-making. Opportunistically such a network is well suited for distributed health management.

Requisite for the proposed approach is the completion of a conceptualized distributed sensing framework, considered by others [5] and currently under development at NASA Ames Research Center [7]. Such a system features interconnected ground nodes with ranged sensors such as vision, infrared, lidar, and radar for tracking vehicles in the immediate airspace. Additionally, weather sensors for tracking wind, gusts, and precipitation also provide micro-climate information useful for scheduling and planning. Ideally, ground-based sensing nodes within this framework would be placed at regular intervals along air corridors, at key corridor intersections, and surrounding vertiports.

This approach is also dependent on the capability of a distributed sensing system to track aircraft within a corridor with a precision necessary for the generation of health management information products including observed stability, conformance to velocity limits, and conformance to airspace volume limits. Previous work by Lombaerts et al. towards aircraft tracking utilizing adaptive multi-sensor fusion in a distributed ground-based sensor setup, taking into account specific properties and limitations of different sensor types, showed the capability of such systems to track a vehicle both en-route and during landing operations [8]. Lombaerts noted that the accuracy of the estimate depends on many factors, most importantly the latency and the number of cameras observing the target, with significant loss of accuracy when less than three cameras are observing the target. Based on these initial results, the density of ground nodes may be driven by requirements for accuracy in vehicle tracking. This capability demonstration in a research environment shows that the some of the technology required to achieve tracking and generation health safety metrics based on position, heading, altitude, and velocity is currently available.

A. Centralized vs Distributed Health Monitoring

Prognostic Health Management (PHM) systems evaluate collected vehicle measurements and produce information products used to achieve goals in both safety and mission assurance. In this process, measurements may first be used for diagnosis of a fault or failure. In addition, diagnostic information is valuable for fault identification and localization, determining what type of fault occurred and what component or subsystem is responsible for the fault. Subsequently, this information can be used for prognosis or the prediction of the future state of the system. Both diagnostic and prognostic information is valuable for decision-making during mission operations and maintenance after the mission. Typically, the systems responsible for collecting vehicle health information, performing diagnostics and prognostics are located on vehicle. As such, it has direct access to relevant measurements and can reliably contribute to closed-loop mission management. However, integrated vehicle health management systems must also conform to size, weight, volume, and power limits and may be subject to faults including sensor errors.

In comparison, distributed health management systems utilize network connected elements across the areas under investigation to produce similar information products. Distributing these elements increases system coverage and resiliency to individual outages, while providing opportunistic monitoring for more targets in addition to the initial targets [9]. Distributed health management also spreads processing required for generation of information products to multiple processors. This architecture is necessary for scaling monitoring operations to air corridor levels where the number of cameras and other ranged sensors could be in the hundreds. Within the distributed health management system, diagnostic and prognostic tasks can be formulated as a particle filter problem to manage uncertainty stemming from insufficient system model fidelity, sensor noise, or unanticipated operating conditions like inclimate weather [10].

B. Health State Estimation for Airspace and AAM Vehicles

While distributed health management systems offer benefits stemming from their network of collected elements, in the case of a distributed ground infrastructure monitoring vehicles in flight, the clear drawback is inaccessibility of onboard data. In certain cases we can assume that operators will opt-in to IASMS services and provide telemetry for the calculation of health metrics [6]. Otherwise, the distributed sensing system must use only the data collected by sensors on the network and aggregated from other network connected resources to make an estimate of the vehicle health state. Such data would come from ranged sensors such as vision cameras, infrafred sensors, lidar, and radar. This section of the paper presents potential vehicle and airspace safety health metrics that produced through collaboration and communication between the distributed sensing infrastructure and the vehicle.

As a vehicle progresses through a flight corridor, multiple ground sensing nodes may observe and estimate the vehicle's position, heading, and velocity. Using this information, a 4D trajectory may be constructed and analyzed for health-safety metrics. A *Vehicle Stability* metric could measure the vehicle's ability to achieve a uniform trajectory through the air corridor and would provide insight into both the vehicle's health state and the vehicle's ability to manage the effects of winds or gusts. Additionally, an estimated 4D trajectory for the tracked vehicle would be valuable for conformance monitoring, ensuring that the vehicle does not exceed speed limits or ensuring that the vehicle remains within the designated air corridor volume, data that is valuable for an *Airspace Safety* metric. The tracking of multiple vehicles and estimate of 4D trajectory for both formations of vehicles and vehicles with different operators can be used for the production of an *Airspace Density* metric. Combined, the 4D trajectory and local weather information from ground sensing nodes could also be used int eh calculation of an airspace safety health metric for *Hazardous Weather*. Finally, information from distributed sensing nodes along air corridors and surrounding vertiports has the potential to mitigate the threat of bird strikes. Wildlife strikes are increasing nationally, 1,800 (1990) to 16,000 (2018), while bird strikes are more likely to occur in rotocraft than fixed wing vehicles [11, 12]. As distributed sensing systems can identify and track not only aircraft but birds too, such a system could produce a *Bird Strike Hazard* safety metric.

IV. Case Studies: Airspace Operations Scenarios

Here a number of case studies are used to evaluate the efficacy of the notional distributed sensing and reasoning infrastructure in UAM operations. Case studies focus on either the vehicle's health state or the health state of the airspace and provide a timeline for observation and diagnosis of health state. Each scenario ends with a discussion of the decisions that are impacted by the produced health safety information products.

*1. **Vehicle Health State Estimation** - Air corridor conformance and unstable control*

In this scenario, a UAM vehicle in flight suffers an undisclosed novel fault in it's propulsion system reducing the vehicle's ability to maintain a desired position or trajectory. The vehicle operator uses onboard fault mitigation methods, but the success of such methods is not immediately clear. The distributed sensing infrastructure in computing the 4D track of each vehicle passing through the flight corridor produces an performance metric for the *Vehicle Stability* and diagnoses an off nominal state.

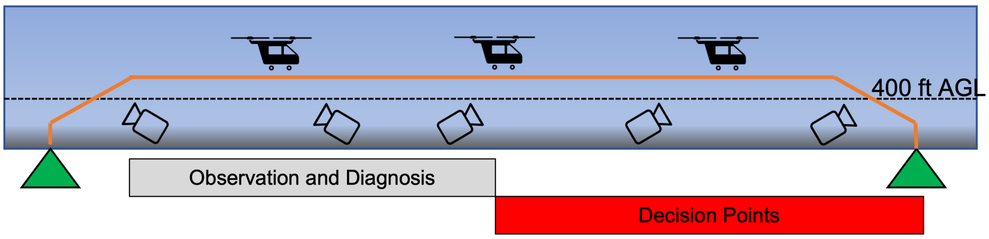

Fig. 2 Scenario #1 - Corridor conformance and unstable control observation, diagnosis, and operational decision making.

Result: a decision must be made as to whether the vehicle can continue to operate autonomously in the designated corridor and potentially approach the vertiport destination. Additionally, the operator must decide whether a remote pilot in command should begin the process of resuming control of the vehicle.

Impact: Here, distributed sensing and reasoning provides advanced warning of potentially hazardous vehicle state, initiating further investigation or potentially a handoff to a remote pilot in command.

*2. **Vehicle Health State Estimation** - Unreliable Onboard Sensor*

In this scenario, a UAM vehicle in flight is progressing along a flight corridor towards its destination. Procedurally, the vehicle connects to the distributed sensing infrastructure to poll tracking and position estimation information for the purposes of uncertainty management. An estimation of the vehicle position is generated from the combined data produced by multiple ground sensing nodes and quickly transmitted back to the vehicle. A large discrepancy between the vehicle's own position estimate and the estimate generated by distributed sensing infrastructure results in a *Airspace Safety* metric as the vehicle can not reliably position itself within the airspace. This vehicle state creates a hazard for other aircraft.

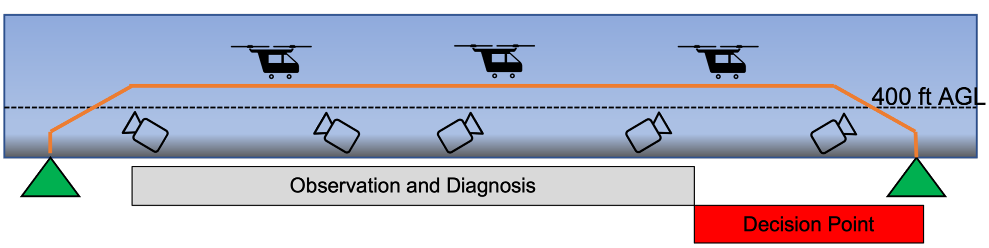

Fig. 3 Scenario #2 - Timeline for diagnosis of vehicle position estimation error stemming from faulty sensor.

Result: a decision must be made as to whether the vehicle can continue to operate autonomously in the designated corridor and potentially approach the vertiport destination. Additionally, the operator must decide whether a remote pilot in command should the process of resuming control of the vehicle.

Impact: This potentially common event plays a important role in the vehicle's state estimation and could lead to diagnosis of an unreliable onboard sensor through cross-validation of onboard sensor systems with the more reliable ground sensing system. In this case, nominal operations benefit from confirmation and uncertainty management for state estimation. Additionally, the distributed sensing infrastructure extends the duration for a remote pilot to gather situational awareness before resuming control if necessary. Critically, off-nominal operation of sensing systems or state estimation errors may be diagnosed before entering vertiport airspace.

*3. **Airspace Volume Health State** - Bird Sighting*

In this scenario, the distributed sensing infrastructure in the vicinity of a vertiport detects and identifies a flock of birds north of the facility and directly in the path of incoming vehicles on a flight corridor. Observation of the flock, determination of their position and heading, and diagnosis of a *Bird Strike Hazard* followed by communication of this airspace risk enables migration operations.

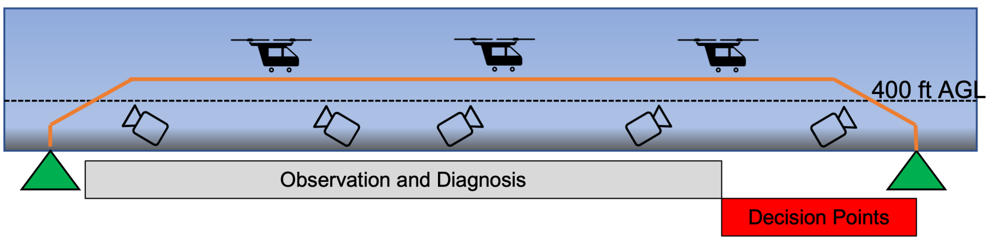

Fig. 4 Scenario #3 - Timeline for diagnosis of bird strike hazard by distributed sensing system surrounding vertiport.

Result: upon receiving the *bird strike hazard* a decision must be made as to whether the vehicle can continue on the original trajectory or take mitigation maneuvers.

Impact: Bird strikes are a serious and growing risk for rotocraft [12]. During direct encounters with a flock, there are limited opportunities for mitigation of this threat. However, as flocks in flight are generally traveling between locations, forewarning and delaying entry to an airspace where birds have been spotted can reduce the risk of strikes. Additionally, the vertiport operator may use this information in the future to implement a wildlife management plan.

*4. **Airspace Volume Health State** - Adverse Weather*

In this scenario, the vertiport is covered in a thick fog, distributed sensing observes the state of the fog and diagnoses a *Hazardous Weather* state. Operators use this information to determine what additional support will be necessary for condition specific traffic patterns and procedures.

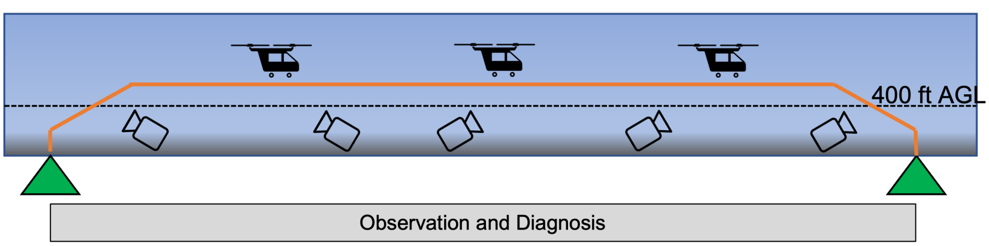

Fig. 5 Scenario #4 - Timeline for Adverse weather diagnosis from distributed sensing.

Result: Knowledge of weather patterns in micro-climates assist in the determination of vehicle perception and navigation capabilities. This information leads to decisions regarding sensor parameters, sensor modalities, and human intervention.

Impact: Distributed sensing provides advanced warning of potentially hazardous airspace conditions, initiating further investigation or potentially a handoff to a remote pilot who will have to manually land the vehicle.

V. Discussion

The above case studies are a simplification of complex AAM operations for the purpose of highlighting the advantages and insight provided by a conceptual distributed sensing and reasoning infrastructure. Within this limited set, information products produced by the conceptual infrastructure assist both vehicle operators and vertiport managers in estimating the health state of the vehicle and the airspace it flies in. In each case, the list of preliminary safety metrics are designed to inform and drive decision-making by either humans or automation tools in support of operators and mangers. Highlighting the case of the unreliable onboard sensor, the distributed sensing infrastructure serves to cross-validate deployed systems even in nominal operating conditions. Additionally, in the case of bird sightings surrounding a flight facility, distributed sensing stands to achieve a more temporal and accurate account of wildlife in the airspace than more traditional radar-based methods. Finally, in considering a UAM maturity level with high levels of operational complexity and high levels of automation, a distributed sensing infrastructure may provide advanced warning of a potentially hazardous condition necessitating remote pilot intervention. In such cases, forewarning of the event enables time to gain situational awareness and make safety critical decisions.

VI. Conclusion

This initial investigation towards distributed sensing and reasoning for advanced air mobility health management and mission assurance is a single thread in a weave representing the quickly evolving field of research and development for AAM. As such, it proposes the use of a distributed sensing infrastructure to benefit AAM operations. The conceptual infrastructure system presented adheres to other prominent research in the field [1, 2, 13]. The described health metrics are very notional and intended to challenge and inspire discussion in the larger community. The simplified operational scenarios presenting in this paper give an example of infrastructure assistance to highly automated vehicles benefiting and the production of health metrics that aid in safety critical decision-making. Future work may include utilization of a simulation framework explore the benefits of the developed methodology, a more detailed calculation of the health metrics, including data description, rate, accuracy, ect., quantification of the benefit of health metrics used in diagnostics and prognostics, and an investigation of human autonomy teaming tool-set and operator tasks to identify opportunities to inject information products from distributed sensing into fleet manager operations.

Acknowledgments

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