

A Decomposition Framework for Describing Advanced Air Mobility Mission Functions

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Several recent key technological advancements have opened the door to new aviation markets and airspace concepts. The success of these new airspace concepts depends on safe and effective use of the new technologies, including the increasing use of automated/autonomous systems. This paper describes the ongoing progress to develop a framework to define, organize and characterize the functions needed to enable the new concepts. The framework must allow the required functions to be described independently of whether the execution of the functions is performed by humans or automated/autonomous systems, flexible enough to allow continued iteration as knowledge is gained, and broad enough to be useful across different aviation domain applications. The framework is intended to help identify barriers to the safe use of automated/autonomous systems in future aviation markets, corresponding research gaps, and data requirements for safety assessment.

I. Nomenclature

AAM	= Advanced Air Mobility
AS-CLT	= Autonomous Systems Capability Leadership Team
CTOL	= Conventional Takeoff and Landing
DGPS	= Differential Global Positioning System
FAA	= Federal Aviation Administration
NASA	= National Aeronautics and Space Administration
TTT-AS	= Transformative Tools and Technologies – Autonomous Systems
UAM	= Urban Air Mobility
UAS	= Unmanned Aircraft System
UML	= UAM Maturity Level
UTM	= UAS Traffic Management
VTOL	= Vertical Takeoff and landing

II. Introduction

The future of commercial aviation will have some of the largest changes in history. The development and introduction of new vehicle technologies may open aviation markets that were previously not viable, and if successful see large increases in the number of aircraft aloft.

A key to the success of commercial aviation as a mode of transportation is its safety record [1], and maintaining that safety record safety is critical to the success of new markets. Historically, a pattern of increased risk has been associated with the introduction of innovative technologies in commercial aviation, regardless of the nature of the innovation (e.g. hardware, software).

These historical trends are illustrated in Figure 1, which shows the accident rates associated with commercial aircraft grouped by generations of similar technological advancements [2]. The figure shows a pattern of initially high rates of accidents immediately following the introduction of a new class of aircraft technologies, followed by a

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decreasing accident rate as knowledge about the new technologies is gained, and mitigations are put in place. There are a broad range of advancements in each aircraft generation, designed to improve performance, comfort and safety.

10 year moving average fatal accident rate by aircraft generation

Accidents per million flight departures

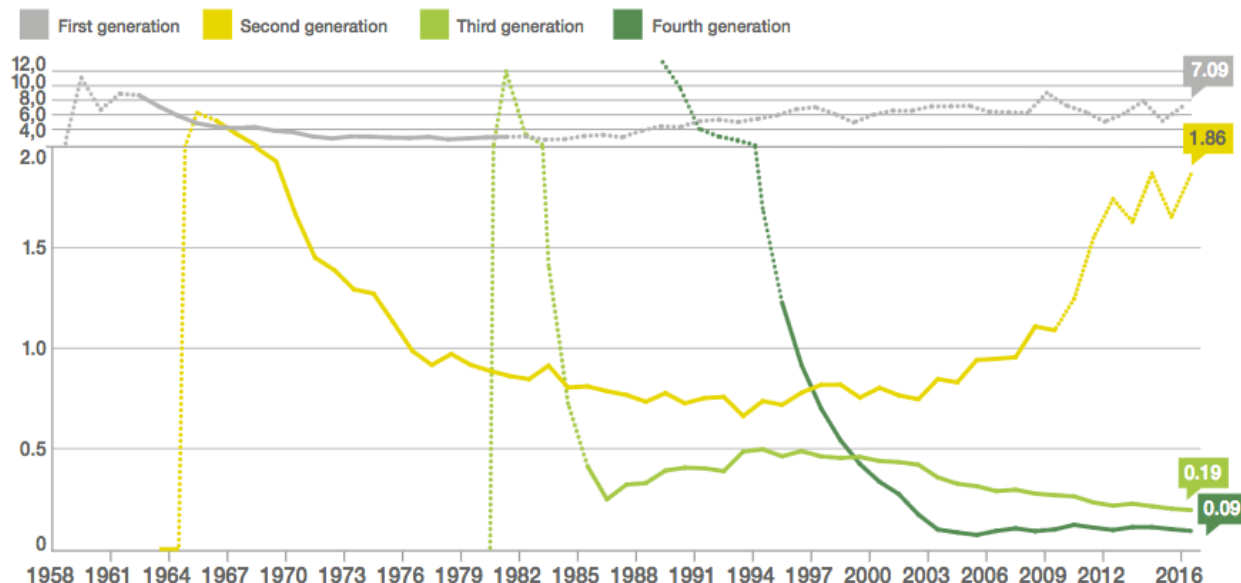


Figure 1. Commercial aircraft accident rates as grouped by similar technologies (credit: Airbus, 2017)

The patterns suggest that even following good design and evaluation practices, it is difficult to predict all of the implications of operating with innovations. The trend also suggests that as new contributors to risks and the causes and contributions to the accidents are better understood, mitigations are put in place to reduce the number of future accidents. This trend places an imperative to better understanding of the implications of the introduction of new technological innovations and new operational contexts.

The success of future concepts is dependent on many different technological advances, but critical to many of these concepts is the introduction of safe and effective automated/autonomous systems. This paper describes an effort to help advance the safe use of these systems by characterizing the functions performed in commercial aviation currently and providing a framework to characterize the functions that are expected to be needed in future concepts.

III. NASA's vision of future airspace concepts, Advanced Air Mobility

NASA's vision for enabling a safe vision of future aviation markets is referred to as Advanced Air Mobility (AAM) [3] as illustrated in Figure 2.

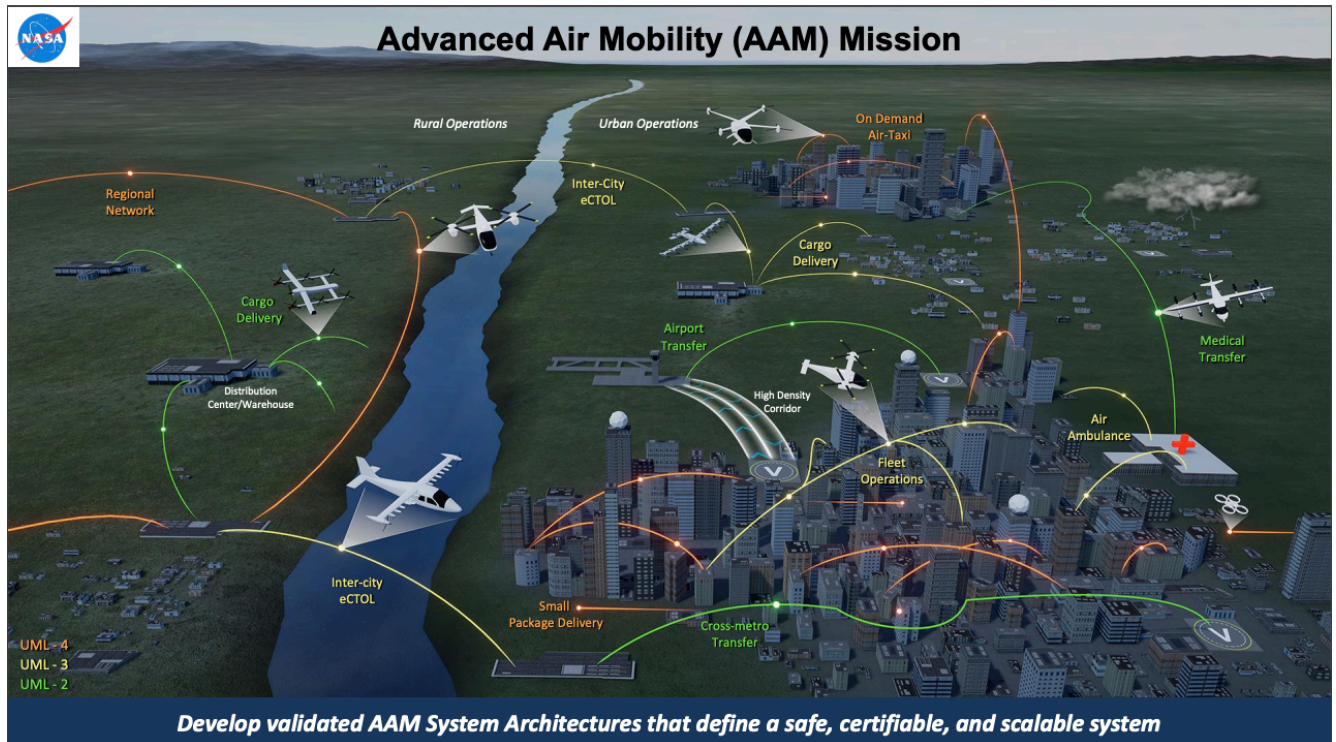


Figure 2. The NASA Advanced Air Mobility illustration

An AAM market of particular interest is referred to as Urban Air Mobility (UAM). The UAM vision, as described by Uber [4] focuses on providing passenger air transportation for short flights within and between metro areas. There are many barriers to safe, efficient and quiet flight in this environment. One of the key technological advances critical to overcoming barriers to the vision of the UAM Operations concept is the increased use of automated or autonomous systems. The expectation is that the addition and integration of the automated systems will improve safety, increase reliability, and reduce human training and operational demands and the associated costs. The NASA UAM concept planning includes a technology maturation chart (Fig. 3) showing the expected progression across the maturity levels to enable UAM [3]. The criteria for progression through each UAM Maturity Level (UML) illustrates the focus on the integration and adoption of increasing levels of augmented/automated/autonomous systems.

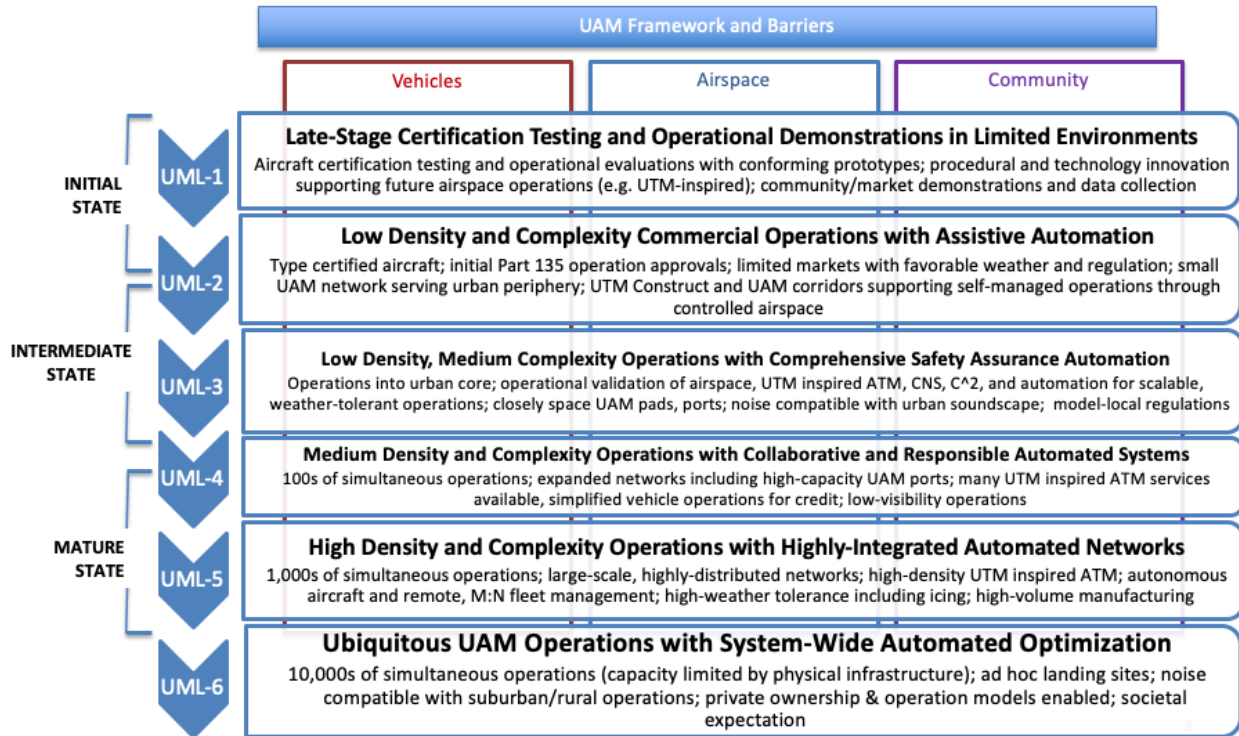


Figure 3. Urban Air Mobility Level (UAM) Maturity Level Progression

An implicit requirement for progression through the UAM Maturity Levels is a means to assess and mitigate safety risks. Safety assessment is a key driver for a means of effectively organizing functions for the transition to the use of automated/autonomous systems.

IV. Functional Decompositions for Autonomy

This paper describes the results of work to define the functions required to safely and effectively operate an aircraft in the Urban Air Mobility (UAM) airspace concept, as part of NASA's Advanced Air Mobility (AAM) vision. The objective of the described effort is to identify and describe all of the required functional capabilities in a manner that is independent from the performer of the function.

To understand the adoption of automated and autonomous systems, several efforts to categorize the functions required to perform missions have been performed. The independence of the function and the performer is critical if the framework is to be useful for designing and assessing the transition of functions from those performed by humans to those performed by automated systems

A. NASA AS-CLT Functional Decomposition

In 2017 The NASA Autonomous Systems - Capability Leadership Team (AS-CLT) started an effort to develop a standardized taxonomy and decomposition of functions required by automated/autonomous systems [5]. The purpose of the taxonomy and functional decomposition was to assess the state of the art of technologies for automated/autonomous systems and determine NASA's capability to address associated barriers and research challenges across the agency. Figure 4 provides the high-level view of the taxonomy.

1.0 Situation and Self Awareness	2.0 Reasoning and Acting	3.0 Collaboration and Interaction	4.0 Engineering and Integrity
1.1 Sensing and Perception	2.1 Mission Planning and Scheduling	3.1 Joint Knowledge and Understanding	4.1 Verification and Validation
1.2 State Estimation and Monitoring	2.2 Activity and Resource Planning and Scheduling	3.2 Behavior and Intent Prediction	4.2 Test and Evaluation
1.3 Knowledge and Model Building	2.3 Motion Planning	3.3 Goal and Task Negotiation	4.3 Operational Assurance
1.4 Hazard Assessment	2.4 Execution and Control	3.4 Operational Trust Building	4.4 Modeling and Simulation
1.5 Event and Trend Identification	2.5 Fault Diagnosis and Prognosis		4.5 Architecture and Design
1.6 Anomaly Detection	2.6 Fault Response		
	2.7 Learning and Adapting		

Figure 4. NASA Autonomous Systems – Capability Leadership Team Taxonomy

The NASA AS-CLT functional decomposition effort solicited input from domain experts across NASA and provides a good starting point for characterizing many automated/autonomous systems functions. The taxonomy does not include analyses of work domain applications for AAM, such as specific vehicle, terminal area or airspace operations.

V. Applied Functional Decomposition for AAM

There are several recent examples of functional decompositions for components of Advanced Air Mobility. The focus of many of these functional decompositions is on the transition from current operations to increasing use of automated/autonomous systems.

Some of the functional decompositions have focused on identifying barriers to increasing the use of automation for airspace management [6]. Many of the pilot functional decompositions [7, 8, 9, 10] have focused on identifying intermediate steps from current operations requiring extensive pilot qualifications (e.g. Commercial, Airline Transport Pilot), to reduced pilot skills, knowledge, proficiency and related reduced training on the way to heavily automated/autonomous piloted aircraft.

While the component functional decompositions provide utility for research of the individual domain applications, there was a need for a functional decomposition for an integrated view of AAM topics, to identify research gaps across the topics, and provide a framework for organizing data requirements. Figure 5 provides an illustration of the overlapping topics areas in AAM.

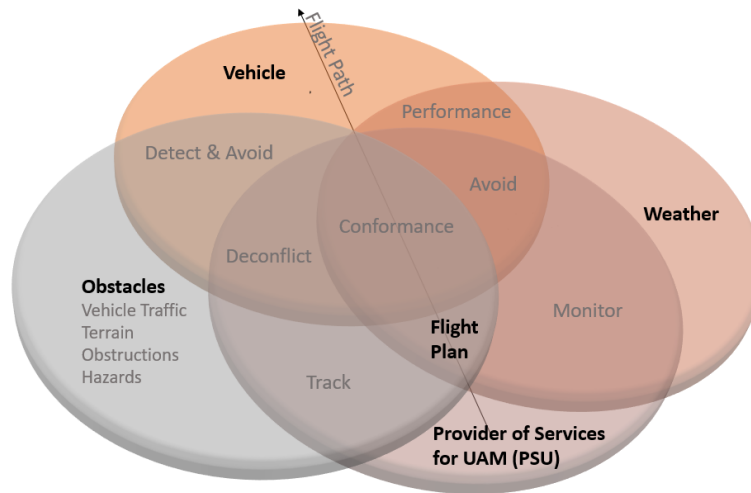


Figure 5. A view of UAM components

In 2019 the NASA Transformative Aeronautical Technologies Program, Transformative Tools and Technologies (TTT) project formed a team[†] to begin to frame the current state of maturity of automated or autonomous systems for use in UAM to support planning for research activities. The results of that effort [11] serve as the initial draft of a functional decomposition to safely and effectively operate aircraft in UAM airspace.

The team started with some qualifications of a functional capability. Based on these, functional capabilities must:

- be observable at the operational level
- perform an intended behavior to achieve a set of desired objectives or goals regardless of implementation or performer (e.g. human or automation)
- refer to a specific action

Based on these qualifying conditions, the team identified nine top level functional capabilities intended to cover all UAM operations. The functional capabilities include:

- [Re] Plan flight
- Aviate
- Navigate
- Communicate with other airspace participants
- Manage Vehicle Systems
- Maintain safe separation (aircraft, weather, buildings, other hazards)
- Maintain consistent flow of aircraft
- Surface Operations
- Fleet Management

A. (Re)Plan Flight

The flight planning functional capability refers to determining a viable flight path that meets the operational constraints for operating a flight. These constraints may include aircraft performance, navigation, weather, passenger comfort and other considerations. The Plan Flight functional capability is performed before each flight but may also be performed in-flight (i.e. re-plan) as well. The function is comprised of several capabilities including:

- Localized, in-time weather prediction
- An understanding of airspace status and structures (e.g. capacity, restrictions) and the implications for flight.
- Communication, Navigation and Surveillance service availability and restrictions
- Scheduling and Resource needs and availability (e.g. personnel, aircraft, infrastructure) for planned and

[†] Homola, J., Gregory, I., and Feary, M. “Functional Decomposition Status Update for TTT-AS”, internal research planning activity, 27 October 2019,

- active operations to optimize across individual aircraft and/or fleet management constraints
- Trajectory generation, Optimized and dynamically updated for mission objectives, mitigation of hazards (e.g. weather, traffic, obstacles) and operational priorities

B. Aviate (i.e. Aircraft Handling)

For the purposes of this decomposition, the Aviate function refers to aircraft guidance, control and (kinetic and potential) energy management to accomplish the mission with the aircraft performance envelope. The Aviate function uses targets generated from the outputs from many other functions, including flight planning, navigation, communication, systems management (e.g. aircraft performance envelope calculation), safe separation and surface operations functions.

C. Navigate

The Navigate functional capability requires accurate and precise sensing for localization and state estimation of the aircraft (or multiple aircraft) - CM and DM are implicit in localization. Navigation also includes calculation of targets to comply with the trajectory generated in the flight planning function and deviations from the trajectory to manage contingencies. Use of historical navigation data may also be required in some instances. IAI is also a cross-cutting capability implicit in the Navigate function with respect to distributed sensing and data repositories for sharing (and learning).

D. Communicate

The Communicate functional capability ensures safe, accurate and reliable communication between all relevant parties in the airspace. Examples of communication functional requirements include phraseology standards, communication scheduling standards and communication of:

- Position/intent/health information (e.g. Airspace participate, vehicle systems, passengers, etc.)
- Diagnostics and Prognostics information for both humans and machines
- Data prioritization

E. Manage Vehicle Systems

Managing vehicle systems refers to understanding the current health and predicted status of all of the aircraft systems and the ability to perform the specific functions. Examples of the technical capabilities include:

- Vehicle management system, including vehicle health management, margin assessment, fault accommodation, vehicle performance constraints
- Vehicle diagnostics and prognostics, including fault detection and isolation, and understanding of the implications of vehicle structural integrity, flight dynamics, performance envelope, system degradation for the mission
- Integrated Power, Propulsion, and Flight Systems, including stability and coordination of Power and Propulsion systems, and the integration of capability and constraint assessments
- Management of passenger/cargo status (e.g. sick passenger, cargo problems)
- Communication of vehicle system states, including continuous performance predictions and trust and certainty of vehicle systems
- Airworthiness & Operational readiness assessment

F. Maintain Safe Separation

Maintaining self-separation is the detection and avoidance of traffic, terrain, wildlife and other environmental hazards, including:

- Strategic deconfliction
- Detection & cooperative avoidance
- Optimized conflict resolution generation based on locally sensed information (i.e. sensor feedback) and/or centralized information (i.e. ATM)
- Sensor and data fusion
- Weather conditions implications
- Obstacle and vehicle sensing information
- Detailed weather information
- Communication and coordination with ATC and/or other vehicles to provide separation (when needed)
- Use of Vehicle trajectory prediction information

- Intent sharing
- Risk envelopes
- Maneuverability
- Reaction time/time horizons
- Conformance monitoring
- Vertiport infrastructure status assessment and management

G. Maintain Consistent Flow of Aircraft

This functional capability focuses on optimizing the flow of aircraft into and out of vertiports. There are many components needed to optimize traffic flow, including:

- Airspace demand/capacity determination (current and predicted)
- Airspace resource allocation
- Vertiport scheduling
- Vertiport status determination and prediction
- Scheduling and sequencing/spacing algorithms
- Equity assessment
- Negotiations at multiple levels (e.g. aircraft, fleet, terminal area)
- Dynamic adjustment of trajectory modification priorities
- Dynamic adjustment of operational and safety envelopes
- Emergent airspace restructuring
- Disruption management
- Conformance monitoring

H. Surface Operations

This functional capability covers safe operation of an aircraft while on (or very near) the ground. For the Urban Air Market this includes aircraft and equipment movement at a vertiport and assumes that any unique aspects of the roles and responsibilities for operations at or near a vertiport have been established. The technical capabilities required for surface operations include:

- Vehicle inspection
- Detect and avoid objects on surface
- Infrastructure inspection and management
- Vertiport infrastructure management (e.g. emergency evacuation)

I. Fleet Management

This functional capability includes real-time monitoring of multiple aircraft for operational purposes. The required technical capabilities include:

- Real-time monitoring and tracking of fleet
- Robust fleet-wide connectivity and communications
- M to N control
- Information/Data visualization (Fleet level to individual operation)
- Operational optimization (Scheduling, Company policy, Airspace restrictions/constraints, Efficiency)

J. Cross-Cutting Capabilities

In addition, the team identified four primary functional capabilities common across multiple functions, included implicitly or explicitly in all high-level functions.

- Information availability and integrity (IAI) to ensure that information is available and trustworthy. This can include issues related to cyber-security, or distributed sensing. Examples include:
 - Authentication
 - Security
 - Cybersecurity of digital data between subsystems
 - Trustworthiness
 - Prediction and Management of data/bandwidth limitations
 - Redundancy/Robustness
 - Resilience
- Information Integration refers to assessing multiple sources of data and combining the data to improve understanding of the current and predicted situation.

- Contingency Management is focused not only on mitigating threats and hazards, but also capitalizing on opportunities for efficient operations and circumventing unexpected changes. Examples of contingencies include preventing, managing and recovering from errors, modify for unexpected operational changes (e.g. passenger or cargo issues) or compliance with special procedures. Special Procedures may include operating into airports with unusual operational conditions (e.g. military airfields, high altitude or surrounded by terrain) or ferry procedures for returning aircraft to a maintenance base. Contingencies also include detection and identification of potential security threats at any point of the flight, pre-flight or post-flight.
- Risk Assessment and Decision Making uses the results of the Information Integration functional capability to assess risks, make decisions, use controls, and monitor results. Risks and hazards may be any combination resulting from the aircraft, environment, infrastructure, external operational pressures (e.g. schedule delays, impending weather concerns) or flight crew (if applicable).

The TTT-AS functional decomposition draft was adopted by the Advanced Air Mobility National Campaign data team as an organizing structure for identifying and defining the required data elements for collection and analysis.

VI. Adding Hierarchy to the AAM Functional Decomposition

The functional decomposition effort performed by the TTT-AS team provided a starting point to support the AAM domain application. It became evident during the decomposition process that the complexity and diversity of the application domains (e.g. aircraft certification, airspace management, vertiport procedures) would require contributions from Subject Matter Experts of varying backgrounds. This led to the need for a framework that could enable function definition and integrate technology assessment across the domains, with an emphasis on supporting the transition to increasingly automated/autonomous systems.

Three structural requirements emerged from the TTT-AS decomposition effort. The structure must allow the functions to be:

1. independent of the performer of the function
2. observable at the operational level
3. traceable to a specific action

These requirements lead to two different perspectives, means-end and part-whole. A means-end perspective allows functions to be defined from the “end” or top-down purpose, as well as from the “means” or physical constraints of the implementation system. This allows the performance “means” of a function to be defined independently of the “end” purpose of the function. A part-whole perspective allows functions to be viewed at different levels of detail, and therefore traced to specific, observable actions. The combination of the two perspectives enables Subject Matter Experts to communicate about the system in terms of goals, while system developers can communicate in terms of concrete details [11].

In 1979, Rasmussen developed a framework for knowledge representation of complex systems [11, 12], combining means-end and part-whole specification. This framework, referred to as the abstraction hierarchy, has been used successfully for characterizing decision-making processes and supervisory control across many domains [13, 14, 15, 16]. Figure 6 shows a summary description of the Abstraction Hierarchy framework.

← Means -Ends → Abstraction	<- Part - Whole ->	Total System	Sub-system	Function Unit	Component
	Functional Purpose	Purpose Based Properties (why) ↑ (what) Physics-based properties and constraints (how) ↓ Aggregation ↔ Decomposition			
	Information Measures and Priorities				
	General Functions				
	Physical Functions				
	Physical Forms				

Figure 6. Abstraction Hierarchy Description

Adapting the Abstraction-Hierarchy framework for AAM provides a mechanism to identify the necessary Subject Matter Expertise for constructing the data requirements. The next section describes the application of the AAM functional decomposition to the discovery of Data Elements for the AAM National Campaign.

VII. Using the Functional Decomposition to Define Urban Air Mobility Data Requirements

The AAM National Campaign [3], is a joint effort between NASA, the Federal Aviation Administration (FAA) and participating industry partners to identify and address barriers to UAM operations in a safe and collaborative environment. Some examples of the challenges facing the UAM concept are research challenges to be addressed in the AAM National Campaign are shown in Figure 7.

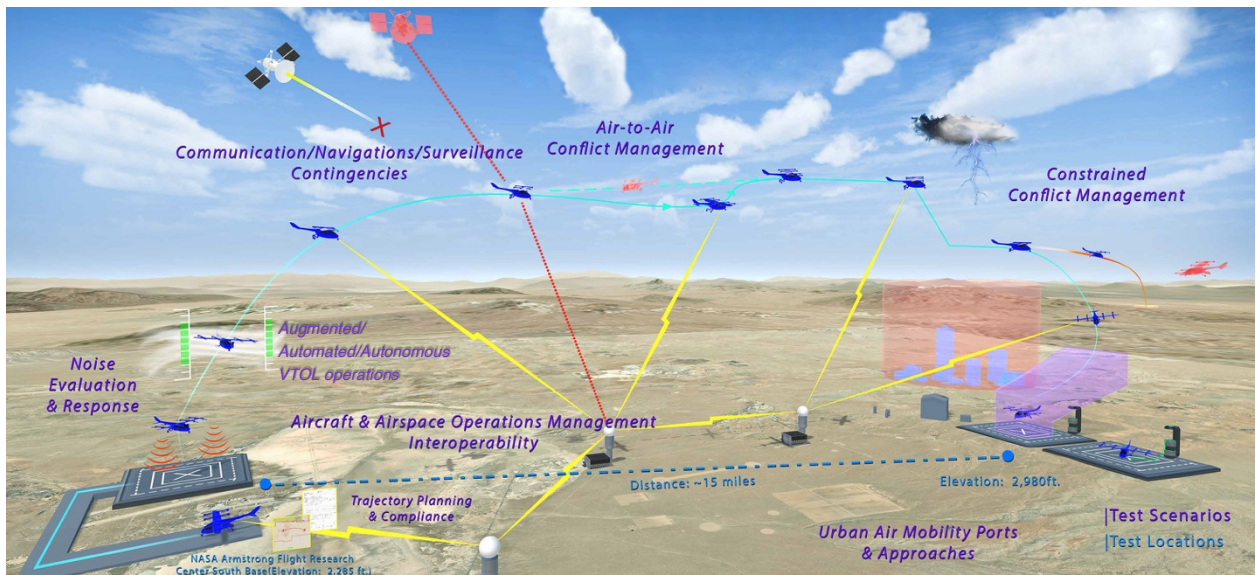


Figure 7. The AAM National Campaign Urban Air Mission research challenge areas

Data collection, analysis and visualization is an important activity for the National Campaign (NC). During NC, data will be collected from live and simulated flight tests with simulations of airspace and vertiport concepts. The data collected will be shared with NASA research projects, the FAA, and by agreement with participating industry partners. By providing a mechanism for collecting data to meet NC research needs, it is expected that the functional

decomposition will provide support for the data management efforts by helping to identify gaps and by placing boundaries around the data needs.

The abstraction hierarchy structure is being used beyond the initial functional decomposition to help specify the data needs for AAM-NC. Table 1 provides an illustration of the Abstraction Hierarchy as applied to the UAM passenger transport safety assessment needs.

←----- Functional – Physical Abstraction -----→ ←----- Functional – Physical Abstraction -----→		← Decomposition →			
		System	Sub-system	Function Unit	Component
	Mission (Functional Purpose)	UAM passenger transport			
	Values and priorities (Abstract Function)		Safety	Nominal Contingency Emergency	
	Entity (General Function)		Aircraft, Airspace, Vertiport	Flight Phase, Metric Type	Metric
	Physical Functions/ Data Element		Aircraft performance characteristic (e.g. stability), Airspace function (e.g. Separate)	DGPS, Barometric altimeter, Radar altimeter	Units, Precision, Update rate
	Physical Form/ Data Formats				aircraft instrument layouts

Table 1. Example of Abstraction Hierarchy applied to AAM-NC passenger carrying mission safety assessment

The framework is being used to help support the data management models and architecture for AAM-NC and will provide a foundation for improving safety through improved data collection and analysis for future aviation safety assessment. A sample of the high-level functional decomposition currently applied to the UAM safety mission is shown in Figure 8.

Mission: AAM Passenger Mission or AAM Cargo Mission
Values and Priorities: Safety, Efficiency, Community Acceptance, Ride Quality
Entity: Vehicle, Airspace, Vertiport, Regulations, Vehicle Operations, Airspace Operations
Data Elements:
Flight Planning: Flight Scheduling, Flight Plan Updates
Separation: Airborne Separation, Surface Separation
Vehicle Location: Vehicle Tracking, Obstacle and Weather Monitoring
Communication: Airspace Providers to Vehicle, Vehicle to Vehicle, Sensor to System
Vehicle Spacing: Maintain Consistent Vehicle Flow, High Density Airspace Scalability and Tempo
Vehicle Performance: Aircraft Stability, Control and Performance Margins, Aircraft Handling Qualities
Decision Making: Operational Prioritization, Energy Reserve Planning
Navigation: Expedient Path, Operational Negotiations
Vehicle Systems Management: Energy Resupply, Mechanical Performance
Community Acceptance: Noise, Location and Volume, Safety and Trust
Contingency Management: Off-Nominal Events, Power Management, Re-Plan Flight
Operations: Timing, Efficiencies and Safety Margins
Maintenance: Vehicle Health Monitoring
Manufacturing: Vehicle and Part Performance
Evaluation/Approval/Certification: Evaluation Task Elements, Procedural conformance limits
Infrastructure: Vertiport and Terminal Operations, Airspace Volumes and Conformance
Information Integration-Availability-Integrity: Calibration, Signal Strength, Accuracy
Registration: Vehicles, Flight Crew, Incident and Accident Prognostics and Diagnostics

Figure 8. Sample Application of the AAM-NC Functional Decomposition

The abstraction hierarchy format shown in Table 1 has been used to capture an initial set of AAM NC data elements. The structure was used to frame interviews and communicate in group discussions with experts in aircraft performance, aircraft certification, Unmanned Aircraft System (UAS) Traffic Management (UTM), vertiport procedure design and other domains across NASA and the FAA. Even the relatively small amount of input thus far has produced a relatively complex set of functions and supporting data elements. The 18 functions listed in Figure 8 are currently composed of more than 1,000 data elements supporting 74 UAM Task Elements and 19 Data Collection Goals and is being used as part of a continual process to refine the data to support research projects to test, optimize and develop safety assessment criteria.

VIII. Discussion

The success of newly conceived airspace concepts depends on safe and effective use of the new technologies. The novelty, complexity and diversity of the concepts will require new methods to assess safety. Defining functions and data needs is critical and foundational to the safety assessment of these new aircraft technologies and airspace concepts. The AAM National Campaign provides an arena to test some of these new technologies, methods of operations and explore new data-driven safety assessment approaches. This paper proposed and explored the initial use of a framework for organizing the functions and data requirements of the proposed Urban Air Mobility airspace concept.

To date the framework has been useful for organizing discussions about function and data requirements with Subject Matter Experts. Past applications of the abstraction hierarchy framework have demonstrated utility as a

framework for identifying barriers to the safe use of automated/autonomous systems and corresponding research gaps and it is expected that this will prove to be true for the AAM application as well.

Methods are also needed for safe progression through the UAM Maturity Levels as the use of automated/autonomous systems becomes ubiquitous. The proposed framework provides a starting point for assessing the UML progression by specifying functions hierarchically, allowing the functions descriptions to remain stable as technological advancements change the means to accomplish the functions.

IX. Next Steps

While the initial test shows that the framework shows promise, the success or failure of the framework will become apparent as the data elements and requirements evolve throughout the National Campaign and associated research efforts.

The framework is being used to support the development of data models and database development for several aspects of UAM, including:

- Flight Inspection data requirements
- Data to support for the FAA Surveillance Broadcast Services Monitor adaptation for UAM
- FAA Safety Risk Management Systems
- Data products such as charts, graphs, statistics and reports for communicating AAM needs within the agency
- FAA risk and safety analysis groups adaptation for advanced air mobility
- Metadata to confirm operations, identify and flag data requiring prioritized analysis, and support hypotheses testing, pattern and anomaly detection
- Data products to inform NASA aircraft, airspace and infrastructure simulation and modeling projects.

Descriptions of the mission and constraints of the environment provide a basis for specifying and validating the requirements for the design of a system, which is critical for assessment of automated/autonomous systems. This enables traceability throughout the design lifecycle and provides a starting point for improved methods for safety and human centered design of automated/autonomous systems [17, 18].

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