

A Data & Reasoning Fabric

to

Enable Advanced Air Mobility

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A Data & Reasoning Fabric (DRF) is envisioned to enable the full potential of advanced air mobility by providing all data and reasoning where they are needed. The DRF marketplace is based on an open foundational ecosystem of data and reasoning exchange between the many systems that must seamlessly interplay to manage the envisioned highly complex and dense airspace operations. DRF activities will identify, test and - as needed - research and develop critical core technologies, and collaboratively test these technologies, open standards and architectures, and the integrated framework with end-users so as to deliver reference designs and development environments that catalyze broad private and public sector buy-in and self-sustaining development of it and associated standards. This panel will discuss some of the critical characteristics of establishing and maintaining DRF and will also address how NASA may be a significant contributor to that effort.

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I. Nomenclature

<i>AAM</i>	=	Advanced Air Mobility
<i>AI</i>	=	Artificial Intelligence
<i>CAS</i>	=	Convergent Aeronautics Solutions Project
<i>COTS</i>	=	Commercial Off The Shelf
<i>DE</i>	=	Disciplined Entrepreneurship
<i>DRF</i>	=	Data & Reasoning Fabric
<i>DMU</i>	=	Decision Making Unit
<i>eVTOL</i>	=	Electric Vertical Takeoff and Landing
<i>FAA</i>	=	Federal Aviation Administration
<i>IoT</i>	=	Internet of Things
<i>IT</i>	=	Information Technology
<i>MIT</i>	=	Massachusetts Institute of Technology
<i>ML</i>	=	Machine Learning
<i>MVP</i>	=	Minimum Viable Product
<i>MVBP</i>	=	Minimum Viable Business Product
<i>NN</i>	=	Neural Net
<i>TACP</i>	=	Transformative Aeronautics Concepts Program
<i>TRL</i>	=	Technology Readiness Level
<i>UAM</i>	=	Urban Air Mobility
<i>UAV</i>	=	Unmanned Aerial Vehicle
<i>UML</i>	=	UAM Maturity Level

II. Introduction

Currently, when data is needed to support airspace operations, typically, the required data sources are identified by human experts, and custom software systems are developed to access or aggregate the needed data into a single software system (Fig. 1). Decision support functions are then built into this software system for the specific airspace application. Each airspace application is addressed the same, resulting in very capable, but isolated, vertical integrations or silos. As we move to more data sources and more airspace applications this approach becomes more and more brittle.

As more data sources are provided by an increasingly diverse range of industries, relying on human experts to remain aware of and make safe decisions from all the relevant and often dynamic data sources will increasingly challenge human capabilities and may heavily constrain air mobility scalability. Much as the early internet evolved from a reliance on a human expert's knowledge of available websites, through human-maintained website lists/books, to self-sustained website catalogs and search engines, access to airspace data sources needs to evolve to be self-sustaining and scalable. It will also be important to provide data customers (for example, a company that wants to provide air mobility functions) the capability to solicit and vet new data sources, as well as to support reliable and consistent exchange and interpretation of data between software systems.

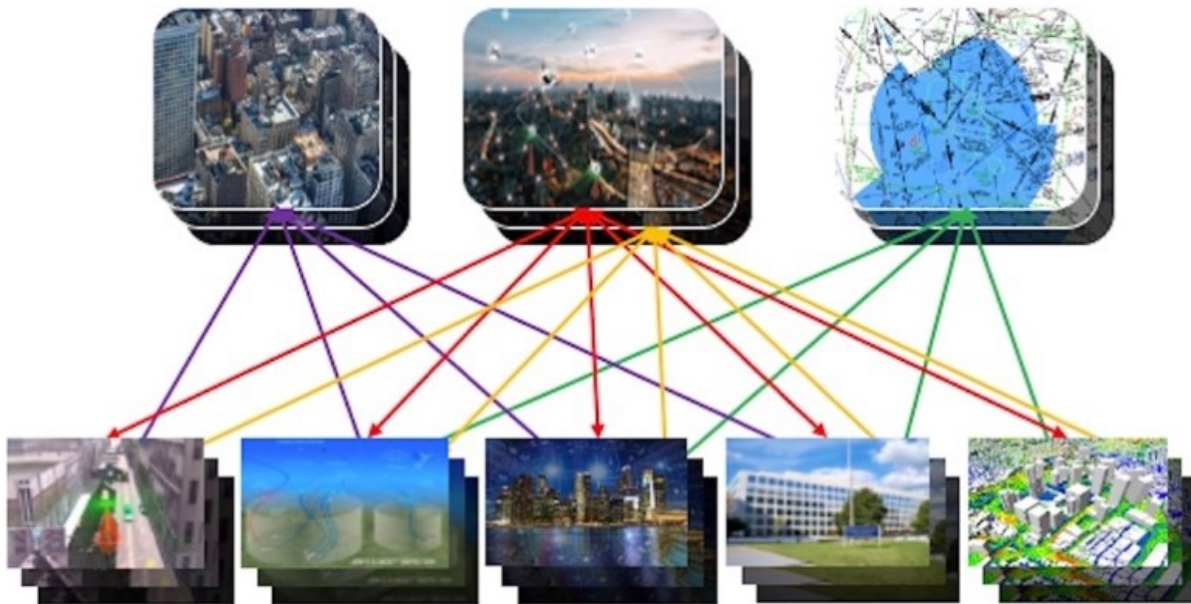


Fig. 1 The Current Trajectory of Air Mobility

A similar scaling issue is arising with reasoning services. Historically, reasoning algorithms have been built into each airspace application. However, reasoning services, ranging from speech recognition services to advanced machine-learning models, are emerging as standalone services. As with data sources, airspace applications need a scalable way to be aware of and integrate this new class of reasoning services. Additional concerns arise related to the current trajectory in that many systemic challenges are not addressed, such as the overall cost of developing many isolated vertical integrations/silos, systematic data quality tracking, and the overall security of the resulting landscape of many airspace application silos.



Fig. 2 DRF Trajectory

The goal of Data & Reasoning Fabric (DRF) is to address these challenges by enabling a self-sustaining marketplace where data source and reasoning service providers can “advertise” their services and data consumers can discover, vet, purchase, aggregate, and use these data/reasoning services to achieve their air mobility missions (Figure 2). This will be accomplished by providing a secure software infrastructure and the tools, protocols, governance and policies to implement, administer, manage, and operate data sharing and reasoning services across all air mobility needs.

In summary, the DRF vision is to enable the full potential of air mobility to improve the quality of human life by providing all data and reasoning where it is needed.

III. Opportunity Assessment

The Data & Reasoning Fabric (DRF) opportunity has been under analysis since late 2018. DRF was presented to NASA Aeronautics in Spring of 2019, at which time DRF was identified as the highest priority new challenge for the Transformative Aeronautics Concepts (TACP) Program’s Convergent Aeronautics Solutions (CAS) Project to consider. The DRF opportunity has been under intense analysis, following a tailored MIT Disciplined Entrepreneurship process since December 2019.¹ The DRF team determined that a modified process was necessary since, for example, some steps/processes are focused on an assurance of a viable money-making company.

In DRF Phase I (from December 2019 to March 2020) the basic question of whether a DRF effort would be of value in achieving the vision of advanced air mobility was posed to representatives of all the relevant market segments. The answer to this question was yes. Next, in-depth market assessments were conducted by both Gartner and a NASA/Venture Capital team to determine the overall market landscape and, given NASA’s core capabilities, what were the specific roles that NASA could and should play in enabling a DRF.

In Phase II (from June 2020 to November 2020), the DRF team sought to understand, in detail, the requirements (captured, for example, in the DRF Tenets of Operations) and available technologies to achieve a first DRF Minimum Viable Product (MVP) and strategies for testing this MVP with representative market segment customers.

IV. Phase I

A. Objectives

In DRF Phase I the basic question of whether a DRF effort would be of value in achieving the vision of advanced air mobility was posed to representatives of the relevant market segments. Next, in-depth market assessments were conducted by both Gartner and a NASA/Venture Capital team to determine the overall market landscape and, given NASA’s core capabilities, what were the specific roles that NASA could and should play in enabling a DRF.

The objective of the DRF Phase I activity was to answer the following questions:

- #1: Does an Air Mobility Data & Reasoning Fabric address the data & reasoning challenges that must be resolved to achieve advanced urban air mobility?
- #2: Does NASA Aeronautics need to do anything, and if so what, to enable an Air Mobility Data & Reasoning Fabric in time to prevent data & reasoning factors from inhibiting progress towards advanced air mobility?
- #3: Given the complexity of this opportunity assessment, are there benefits to following a disciplined entrepreneurship process to assess this opportunity?

B. Approach

There are unique complexities to the DRF opportunity, including:

- Success is characterized by facilitating the emergence of a self-sustaining commercial DRF marketplace with appropriate industry, government, and academic roles. This is a more outward-facing opportunity than, for example, maturing a technology for eventual use on/in a NASA mission or by government partner.

- DRF can best succeed by having an in-depth understanding of the relevant commercial IT and aerospace technologies and trends. The focus of DRF is on the viability of a technology stack to provide an increasing and relevant capability for advanced air operations, with individual technology layers being swapped in/out as the foundational IT technologies rapidly progress.

These unique complexities require a formulation process that focuses on NASA priorities, but is informed by a deep understanding of commercial practices, priorities, technologies, and trends. It is also important, because of the extensive engagement with industry, that the DRF Team uses a vocabulary and process that is common in industry. Entrepreneurship processes meet these needs. There are many, mostly hosted by major universities, such as MIT, Stanford University, and University of California Berkeley. The MIT Disciplined Entrepreneurship process is among the best documented with an impressive history of success. MIT alumni have started over 25,000 companies (900 per year), employ 3+ million people, with annual revenue of ~\$2 trillion.¹ A tailored MIT 24-Step Disciplined Entrepreneurship process was used to answer the three questions outlined in the objectives. For Phase I, the following MIT Disciplined Entrepreneurship steps were used:

- Step #1: Market Segmentation
- Step #3: Build an End User Profile
- Step #7: High-Level Product Specifications
- Step #10: Define Your Core
- Step #20: Identify Key Assumptions
- Step #22: Define the Minimum Viable Business Product (MVBP)

A DRF Team was established that included NASA civil servants with airspace, vehicle, software, data, reasoning, and communications expertise and Venture Capitalists that added expertise in airspace and air mobility opportunities and economics. Gartner was contracted to provide a vendor map for the DRF technology ecosystem, allowing the identification of gaps, especially the ones that NASA could and need to fill and create a value model to project the impact and assess the growth opportunity of DRF.

C. Accomplishments

The DRF Team interviewed 13 potential end-users, spanning the relevant range of aerospace, avionics, and aerospace industries, information technology (IT) companies that are candidate providers of relevant IT technologies, and government entities ranging from local governments, state governments, to NASA and Federal Aviation Administration (FAA) stakeholders. From these interviews, end user characteristics were identified, including:

1. FAA is assessing its next evolution of data/management systems
 - Assessing what the architecture of its next evolution of data/management systems should be (5-10+ years).

DRF work could inform and influence FAA future data architectures.
2. Aerospace Industry is laser-focused on solving the problems they perceive they can solve
 - Companies are currently focused on providing an MVP which they can deliver with the technology in hand, to a viable market, with a concept of operations within current regulatory environment.

Aerospace Industry is looking for and exploiting “lowest hanging fruit” opportunities, not looking to solve the hardest problems. Most acknowledge technical, role, and regulatory challenges to achieving out-year MVPs. Industry seeks clarity on airspace data requirements, architecture, and standards to clarify out-year MVP planning and to unlock investments and commitment of resources.
3. IT Industry perceives the air-mobility data & reasoning challenges as other big-data and/or IoT opportunity
 - Aerospace industries are going to IT industry leaders to acquire either technology stacks or acquire vertical solutions.
 - IT industry (Big-Data/Data Analytics, Edge-Computing, IoT, etc...) believe they have relevant technologies for DRF.

There appear to be unique challenges of a very broad and dynamic set of data sources and stakeholders. Safety considerations appear to be present a challenge to simple re-application of existing IT stacks yet ignoring those stacks would be ineffective and represent a missed opportunity to leverage baseline technologies.

4. Governments see the need to manage their transportation infrastructure, including their airspace
 - Some governments see improved mobility as a competitive advantage, others a quality of life priority.

Enabling air mobility is a priority. Local governments are proceeding despite lack of a solid regulatory environment, using best available data and tool sets to make infrastructure investments.
5. Governments will only mandate data sharing as required for safety or optimal use
 - Governments are hesitant to require data sharing beyond what is required for safe and optimal use of airspace or infrastructure assets. Beyond that, it is perceived that data sharing requirements may inhibit investments and growth.

Different levels of data sharing must be supported. Expect minimal data sharing with regulatory bodies to support safety, with more data sharing potentially required for operational safety and/or efficiency between operators, service providers, and local governments.
6. Industry, generally, perceives data as a valued asset to be shared only as required or to create and capture value.
 - Data, beyond government supplied data and regulations, will only be provided as required or as perceived as improving a relative business position, or for profit.

Any ecosystem to encourage data sharing must enable a business-based ecosystem to encourage data sharing among industry and thereby, greater participation by industry. Data will not be shared unless required or value-creating.
7. Industry bifurcates on data sharing, with the largest companies preferring to pursue a “mono-ecosystem,” while other companies prefer an “equal-access ecosystem,” and local governments want optimal use.
 - Large companies prefer to own all data, to the exclusion of competitors, but will acknowledge challenges to being responsible for entire urban ecosystems, which local governments prioritize.
 - Smaller companies prefer an open ecosystem in which they can prosper by having many customers.

A virtual data ecosystem may best serve all stakeholders, providing best use and profits, hence ecosystem growth. This aligns with past precedents in similar technology areas.
8. Current MVPs and Concept of Operations do not rely on AI beyond NN feature/object detection
 - Neural Net (NN) based feature/object detection is an accepted capability; beyond that, deterministic trajectory and operational decision advisory processes are the accepted baseline.

AI, beyond commercial off the shelf (COTS) based NN, are not commonly baselined in current industry MVPs.
9. Industry acknowledges that transition from 1:1 to 1:N human: unmanned aerial vehicle (UAV)/ electric vertical take-off and landing (eVTOL) operation is fundamental to increased profit margins and system utility, eventually with humans performing fleet management off-vehicle.
 - Transitioning to high-rate operations in dense urban environments requires an increase in the number of machine-intelligence based decisions (with human oversight) or the system will be constrained by human capabilities.

Transition from 1:1 to 1:N human/UAV-eVTOL operations will require an increased use of AI, but the trajectory and technologies of this use is unclear. DRF foundation must be agnostic and able to support either or both.
10. Following big data/data analytics trends, a next use of AI may be to vet and enhance data/reasoning quality.
 - Increased use of 2nd party data for operational decisions will require some measures of data quality, including but not limited to, reliability, fidelity, and currency, attributes often best characterized by AI systems.
 - Data (and learning AI systems) may require automated, real-time certification, to assure up-to-date accurate understanding of data and reasoning attributes and qualities.

The next use of AI to advance air mobility may be in data/reasoning vetting and data/reasoning service recommendations.

D. Takeaways / Lessons Learned

#1: Does an Air Mobility Data & Reasoning Fabric address the data & reasoning challenges that must be resolved to achieve advanced urban air mobility?

- Current Advanced Air Mobility MVPs do not rely on any technologies beyond those in hand and integrate systems in ways highly specific to the MVP end application.
- No company acknowledges a dependency on any NASA aeronautics technology for current MVPs, including a Data & Reasoning Fabric.
- However, discussions with government and industrial stakeholders beyond current capabilities and foreseeable MVPs generally acknowledge:
 - An “air-gap” between current data & reasoning capabilities and what will be required to enable dense urban air-mobility, especially passenger-carrying vehicles, with move to 1:N human/eVTOL operations and the human off-vehicle.
 - A need for a generalized and extensible solutions to support high density air mobility achieved by a proliferation of end applications and operators.

A refinement of the Data & Reasoning Fabric concept and targeted work in specific areas would create a better understanding of how, from a data and reasoning perspective, the advanced air mobility vision can be accomplished.

#2: Does NASA Aeronautics need to do anything, and if so what, to enable an Air Mobility Data & Reasoning Fabric in time to prevent data and reasoning factors from inhibiting progress towards advanced air mobility?

NASA work in the following areas has been identified as being both

- Required to achieve the UML6 (NASA’s UAM Maturity Level 6 (UML6) indicates ubiquitous UAM operations with system-wide automated optimization) (from a data and reasoning perspective), including consideration of discovered government and industrial efforts.
- Appropriate to NASA ARMD’s role and demonstrated competencies.

Data

- For a set of UML6 Concepts of Operations, what data needs to be available to which decision-making entities (e.g., vehicle, airspace, and infrastructure decision authorities), and what are the “ilities” of the data that need to be defined to support the appropriate use of the best data?

Architecture

- What architecture can best support cost-effective, efficient, decentralized and low-latency data sharing which is needed for high-density and safe urban air mobility, while also encouraging a viable and growing “open-ecosystem” commercial data economy?

Roles

- With regards to data, including infrastructure use and airspace regulatory data, what are the roles of all the stakeholders, ranging from vehicle providers, UTM-providers, mobility-as-service providers, infrastructure owners, and local-to-federal government entities?

Prototype/Demonstrations

- The advanced air mobility vision needs to be supported by a complex system-of-systems fabric that has never been deployed before.
- Specific advances need to be prototyped, and – periodically – tested in large scale system-of-systems demonstrations so as to increase the TRL level to allow industry to extract and use advances in future MVBPs.
- Demonstrations identify technical and operational capabilities/deficiencies and help to explore and refine requirements.

1:1 to 1:N Use Cases Analysis to Data/Architecture Needs

- It is generally recognized that machine-based decision making (with human oversight) will be required to achieve 1:N operations. What, specifically, does the Fabric need to provide to allow integration of machine intelligence to allow specific 1:N concepts of operations?

Note: Between Phase I completion and Phase II initiation, it was also identified that NASA needs to take steps to characterize the communications capabilities available to support DRF, especially wireless

communications, as communications capabilities will have a strong impact on the overall data, reasoning, and software architectures.

#3: Given the complexity of this opportunity assessment, are there benefits to following a disciplined entrepreneurship process to assess this opportunity?

Advantages of DE are that it provides a very detailed process focused on understanding and designing products to customer/market needs. Frequently the DRF Team found the DE process pulling them back to gather additional information regarding:

- Customer/market for DRF
- Industries' perceived role of NASA related to DRF
- IT industries ecosystems that DRF needs be aware of and make best use of
- Aerospace/Airspace ecosystems that DRF needs to blend with

In addition, DE provides a framework and “vocabulary” for quick and in-depth engagement with industry. Specifically, DE provides a common language with industry, which is very helpful in allowing NASA staff to understand industry processes and for NASA staff to explain ourselves to industry.

Challenges of DE is that it includes some steps/processes focused on assurance of a viable money-making company. For this reason, the DRF team needed to tailor these steps either by shifting measure of value to national benefit or excluding those steps.

DE is a proven and detailed framework for designing products in response to customer/market needs. The DRF team would recommend continuing to use DE to assure a continued focus on customer/market needs and the many industry-NASA touch points critical to DRF success.

V. Phase II

A. Objectives

The DRF Team had three objectives in Phase II:

- Establish the Scope of a DRF
 - Target DRF for operations in the UML-6 environment. However, there currently are not well-defined concepts of operations for UML-6. As a result, the DRF team developed a set of Tenets of Operations, in order to help inform an initial DRF architecture.
- Identify technologies and best practices for building a DRF
 - Down select to initial technology stacks from current and emerging foundational IT technologies
 - Determine industry/marketplace best practices that can be adopted or leveraged by DRF
- Recommend an initial DRF architecture
 - Define prototyping activities and community best practices required to mature the DRF technical approach
 - Develop strategy for testing DRF assumptions through end user engagement with DRF prototype

B. Approach

For Phase II, the following MIT Disciplined Entrepreneurship steps were used:

- Step #5: Profile the Beachhead Market Persona
- Step #9: Identify Your Next 10 Customers
- Step #12: Determine the Customer's DMU
- Step #20: Identify Key Assumptions
- Step #22: Define the MVBP

The DRF team gathered requirements from stakeholders in industry and local governments. This helped establish marketplace and business requirements. Also, with a view on UML-6 and FAA / NASA Vision 2045, the DRF team developed a set of Tenets of Operations (Fig. 3). The Tenets of Operations were used to inform the development of the DRF MVBP.



Fig. 3 Phase II - DRF Approach

C. Accomplishments

As shown in the figure below, the DRF team developed Tenets of Operations, gathered the needs of the community and developed a reference use case to inform the DRF MVBP design requirements.

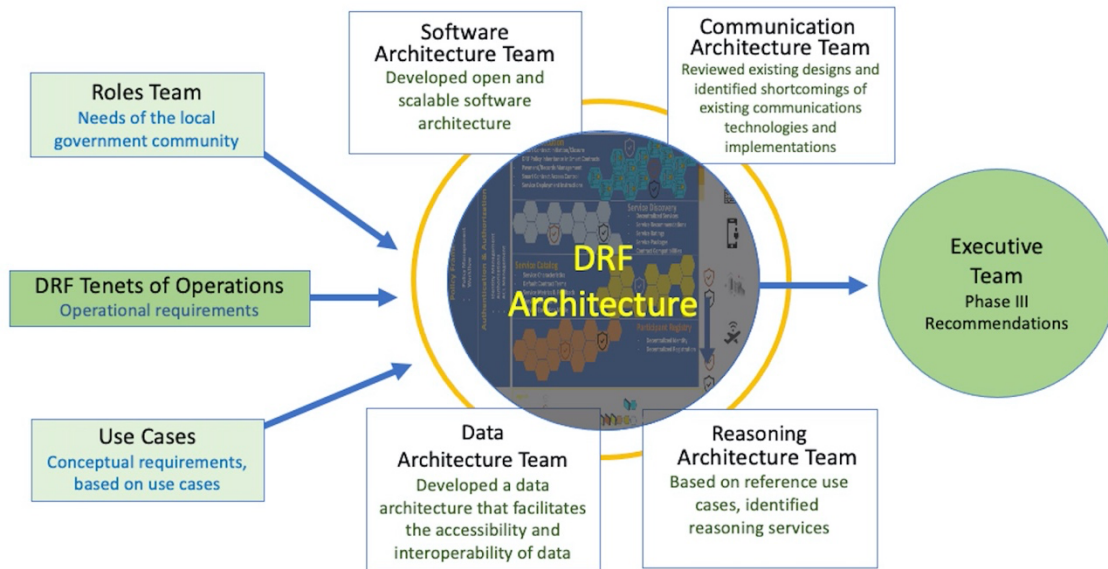


Fig. 4 DRF Phase-II Accomplishments

The DRF software team developed an open and scalable architecture that will be the core of the MVBP. The DRF data team a data architecture to facilitate data interoperability. The DRF reasoning team identified reasoning services that are aligned with nominal and the documented use case. The DRF communications team identified shortcomings of existing communications technologies, as it relates to the requirements of advanced air mobility.

D. Tenets of Operations

The DRF team established a set of overarching tenets that establish the *Why-What-How* of the effort, as shown below:

[WHY]: DRF IS FOUNDATIONAL LEVERAGE FOR THE SYSTEMS THAT SUPPORT COMPLEX AND UBIQUITOUS AAM OPERATIONS (INCLUDING UML 6):

The Advanced Air Mobility (AAM) community has an enterprising vision for our future airspace system, the implementation of which will be challenging. Supporting increasingly complex and dense safety-critical flight operations involves a substantial system engineering and data/knowledge engineering challenge, some aspects of which are unique to the airspace system. There are stringent requirements for safety, data exchange, security, and for communications between systems. Applying lessons learned in recent decades of software development and the Internet, this is best approached with a carefully designed foundational framework that robustly and consistently implements critical core functions and defines common interfaces, protocols, or standards, providing powerful leverage to those who extend it and build on top of it. Such a framework also democratizes the AAM airspace ecosystem, reducing the chances for monopolistic market dynamics to emerge.

Further, the ultimate uses of the airspace system, and thus its requirements, are not fully known. It will be continually extended, and many parties will contribute innovations and/or support operations. A common foundation will not only improve the quality of the systems supporting the airspace system, but its extensibility will be instrumental to allowing this and to realizing the full potential of advanced aerial mobility.

DRF will be for advanced air mobility what HTTP, HTML, and XML were for the Web.

[WHAT]: DRF IS A MARKETPLACE FOR DATA AND REASONING SERVICES FOR ALL AAM STAKEHOLDERS:

DRF is a set of secured software infrastructure, tools, protocols, governance, and policies to implement, administer, manage, and operate data sharing and reasoning services across the entire span of air mobility and other smart edge nodes. DRF should be thought of as a set of powerful and common tools with which others can more easily build their parts of the future capabilities for the airspace system. With a foundational ecosystem such as DRF, these capabilities can be implemented with more consistent quality, more robust real-world performance, better interoperability, better security, and greater future extensibility.

DRF INCLUDES AND SUPPORTS A TRUSTED MARKETPLACE: Recognizing that the private sector will deliver the innovations to build on top of DRF to bring new capabilities to the airspace system, and that the private sector will continually expand the uses and capabilities of the airspace system into the future, it is important that DRF serve as a foundation for an economically self-sustaining system of data creation, exchange, insight, and action. This will encourage private-sector participation alongside appropriate government and academia engagement

DRF succeeds if it supports a vibrant business ecosystem with foundational support for the economically viable participation of all relevant industry sectors, as well as the minimal appropriate participation by government to assure the equitable, safe, and secure operation of the national airspace and supporting infrastructure. To the extent possible, academia should be allowed far reaching access to DRF to support their research in the effective operation of the national airspace.

[HOW]: DRF IS FLEXIBLE AND APPLICATION/MISSION-AGNOSTIC, BUILT ON THE SHOULDERS OF CURRENT AIRSPACE CAPABILITIES:

It must have a generalized framework, be inherently extensible, and enable appropriate adoption and plug-in interoperability across open standards and technologies. DRF must be backward-compatible with existing airspace systems and infrastructure, as well as extensible to other modes of transportation.

DRF will evolve based on current best practices and technologies, with a preference for open standards, technologies, and architectures to assure equal access to the DRF business ecosystem by all viable data and reasoning providers and use by all data and reasoning service users.

DRF will wrap current capabilities so as to allow their seamless integration in the emerging DRF standards, technologies, and architectures. This might entail converting existing “human readable” information into “machine consumable” data. No capabilities will be lost, only refactored for integration in to the DRF, as

driven by the effective operation of the national airspace. DRF will facilitate a spectrum of human oversight and decision-making assistance.

Recognizing the evolving nature of the AAM ecosystem and anticipating the “unknown unknowns”, DRF will be designed to allow additional capabilities to be added seamlessly without the need to redesign the core architecture.

The DRF team also established eleven functional tenets to inform the MVBP.

DRF DATA TRUST AND CONFIDENCE: DRF shall provide all stakeholders the ability to express, transmit, and consume information regarding the quality of data. Data quality attributes (metadata) shall be extensible in definition and can include support of safe, secure, efficient, and reliable operations within the airspace system.

DRF SAFETY: DRF shall enable safety-critical operations through framework functionality required for systemwide coordination across data trust and confidence, communications performance, and responsive policy definition/implementation, as well as other areas that support airspace system safety goals.

DRF COMMUNICATIONS: DRF shall support a robust, resilient, timely and dynamic communications environment that supports communications service discovery and variable performance requirements all while meeting the DRF community access requirements.

DRF RESILIENCY: DRF shall be able to support definition of adaptive systems and maintain its intended functionality when faced with off-nominal conditions, or otherwise will be able to support appropriate policy response, at both the infrastructure level and the application level, and communicate to stakeholders.

DRF SECURITY: DRF shall provide a secure environment that supports (1) mechanisms to identify the cyber risks, vulnerabilities and weaknesses of the environment, (2) secure data exchange and service interactions by maintaining secure data integrity, system resiliency and information privacy, (3) mechanisms for monitoring and detecting malicious or abnormal behavior and (4) effective countermeasures needed to take regarding a detected cybersecurity or physical event.

DRF REASONING: DRF shall enable resilient 1:N increasingly automated operations via a marketplace of decision-making services that provide logical sequences and predictions in a robust and timely fashion.

DRF DATA TYPES: DRF shall support definition of formats for common data elements and full lifecycle support for their extensibility. DRF shall support extensible definition of metadata to enable evaluation of data and inform its viable uses.

DRF DATA FLOW AND ACCESS RIGHTS: DRF shall implement a framework to support discovery of data sources, evaluation thereof, and transactions to acquire data flows protected via appropriate access rights.

DRF IN-TIME PROCESSING PERFORMANCE: DRF shall facilitate the discovery and allocation of resources for data, communications and computing as required for in-time data processing.

DRF POLICY FRAMEWORK: DRF shall support definition of policies and procedures encompassing relevant operating rules for the airspace system. DRF shall support the propagation of policies and procedures across the DRF ecosystem with consistent interpretation and appropriate execution by all nodes. DRF shall support mechanisms to establish feedback loops on policy compliance and deviations, with appropriate system-wide responses for both nominal and contingency circumstances.

DRF REASONING TRUST AND CONFIDENCE: DRF shall provide all stakeholders the ability to express, transmit, and consume uncertainty information related to the reasoning system, its logic, and the input data attributes such as availability, quality, safety, and security.

E. Roles

After conducting several DRF stakeholder interviews in Phase I, we identified a gap in our data-gathering related to local government stakeholder representatives. It is recognized that local governments will be vital stakeholders due to their role in data usage and provision. Therefore, we carried out interviews with representatives from a variety of local governments and gathered information regarding their data needs, priorities, collaborations, and role of NASA in AAM data exchange.

Takeaways / Lessons Learned

Based on the interview results and our analysis and findings above, the major takeaways/lessons learned in our studies on the roles of state and local governments in DRF are summarized in the following:

- Many types of data are being collected by state/local governments, especially on surface traffic. But many disparate and sometimes home-built data systems exist, with little connectivity across governments (e.g. state-to-local).
- Safety is the highest priority in data collection and applications for all the state/local governments all the time (in the past, at present, and in the future).
- While some standards and data sharing exist, they are sporadically applied in many cases. There is a clear need for more standardization and a call for more mechanisms and technologies for data sharing across the governments and industries.
- Privacy introduces complex issues. While the local/state governments claim that the required and necessary measures have been taken to prevent violation of privacy and data securities, it will still be a critical issue in data collection, sharing and applications in the future.
- Some governments are beginning to collect and connect new modes of transportation data (e.g. scooters). Inter-modal connectivity, both with data and people, is of great interest.
- Use of advanced data techniques (e.g. AI/ML) is sparse but evolving. Many local/state governments recognize the importance and usefulness of AI/ML technologies and feel very interested in applying them, but don't know how.
- While seeing the AAM revolution on the horizon, very few local government representatives have documented plans to incorporate aviation data as yet and many underestimates the regulatory environment of aviation.
- NASA is seen as an honest broker concerning data usage and distribution in the AAM realm, can help foster necessary partnerships, and can also help develop and maintain AAM software platforms.
- Industry is positioning itself as a technology provider and desires to be partnered with state and local governments in AAM development
- There is a need to conduct a "gap analysis" and more in-depth case studies with at least two local/state governments to identify the needs and roadmap to a future UAM/AAM with robust data fabric capabilities. This work will also help maintain the necessary relationship with local governments to insure AAM relevance to the broad user community.

F. DRF Software Architecture

The overarching goal of DRF software architecture is to create the necessary mechanisms and abstractions to support complex operations among and within the smart airspace, smart cities, smart vehicles, data services, compute services and service consumers. In order to accomplish this goal, the software architecture team evaluated and used a range of proven methods, practices and architecture patterns to develop and organize the software architecture components. The team also evaluated capabilities of existing data platform solutions using DRF use cases and tenets of operations. Careful analysis of the use cases and the assessment of existing capabilities led us to develop software architecture for a real-time data and reasoning marketplace with a decentralized data backbone that is needed for future aviation. The software architecture development was primarily focused on four key drivers: usability, availability, performance, and security.

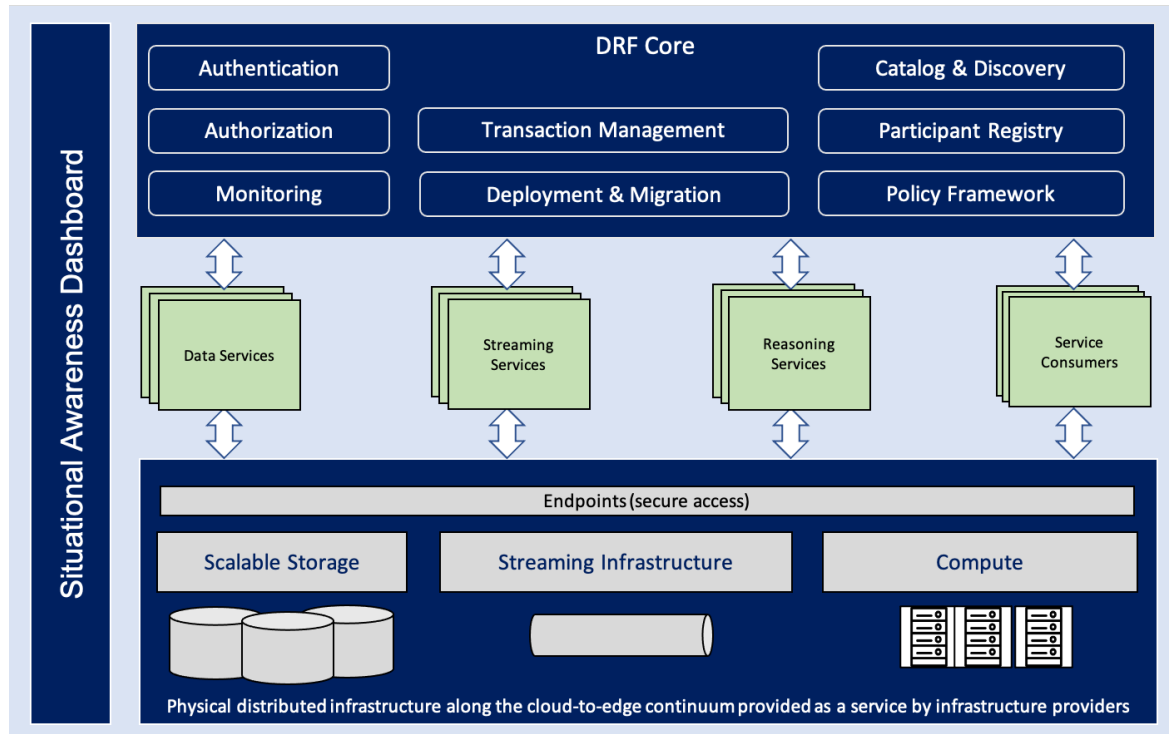


Fig. 5 DRF Software Functional Architecture

Fig. 5 shows the software functional architecture of the DRF marketplace. The architecture is comprised of various functional requirements as core capabilities including management of participants, resources, transactions, security and policies. It enables participants to register and discover data and reasoning services and provides integration with the services across the cloud-to-edge continuum. The participants include data services, reasoning services, and service consumers. Physical infrastructure along the cloud-to-edge continuum, available as a service from infrastructure providers, is used to support the data storage and streaming and computing requirements necessary for data and reasoning services. All transactions within the system are secure and encrypted to ensure the safety and integrity of data exchange.

Takeaways / Lessons Learned

The goal of good software architecture is to help manage complex systems. This section highlights key software architecture takeaways and lessons learned.

- The UAM industry needs a marketplace to enable data democratization and, thereby, wider participation.
- Traditional data platforms will not meet the needs of AAM data exchange due to the known challenges including lack of neutrality, privacy and vulnerability to cyber-attacks. A real-time data and reasoning marketplace with a decentralized data backbone is needed and will be transformative for future aviation. Other industries including autonomous vehicles, manufacturing, smart cities are also moving towards a similar approach.
- The *DRF* software architecture effort is certainly worth pursuing since currently there are no such architectures in the UAM sector, and most companies involved in the market are building siloed solutions.
- Several architectural concepts that were tracked were only applicable to certain situations. Therefore, they do not have a natural progression across the adoption curve. Examples include centralized data pipeline and centralized data warehousing.
- New software architecture trends to watch for include Data Marketplaces, Data Meshes, Smart Contracts, Compute to Data, Edge and Fog Computing, and Policy as Code. The variety of purposes shows that innovation is occurring in many different areas in the architectural landscape, which will support the software architecture road map.

- A data marketplace can collectively create massive value by pooling data, yet with controls that maintain value through access rights and permissions. More companies are looking at the fundamentals of correctly built distributed systems with the idea that they may need to transition to a data marketplace at a later date.
- Industry adoption is essential for the success of *DRF*. The data marketplace approach is a new trend, which may lead to initial resistance with *DRF* adoption. Therefore, it is essential to have a strong execution on the architecture implementation coupled with advertising effectively to industry to co-opt them into supporting *DRF* and driving it forward.

G. DRF Data Architecture

The data team conducted a series of interviews with the AAM stakeholders, subject matter experts, and market analysts to understand the *DRF* ecosystem and the value add to the individual user groups.

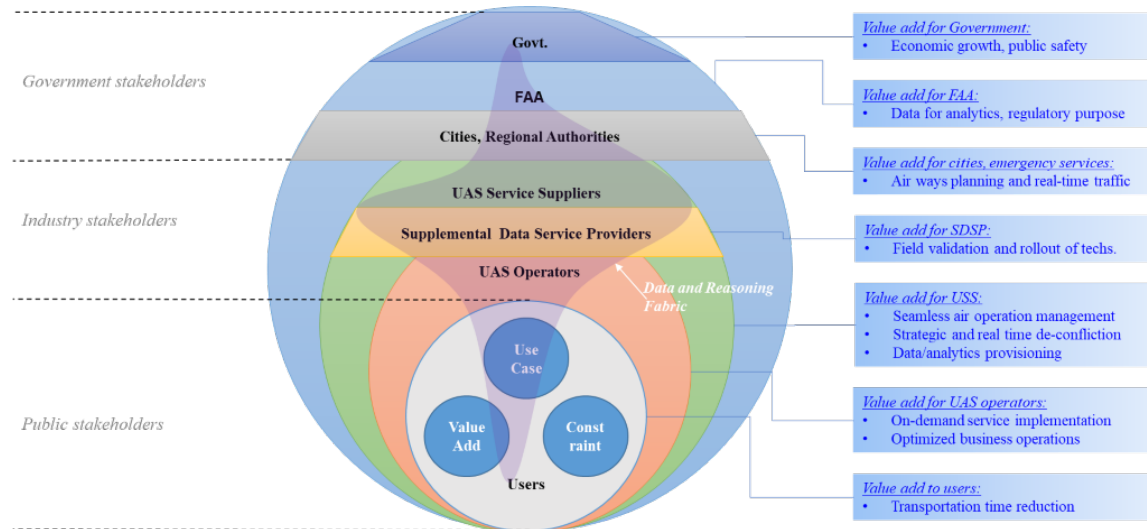


Fig. 6 Value add to the DRF ecosystem

The data produced, traded, and consumed by this diverse ecosystem is correspondingly complex and the data functionalization model has multiple facets to it. Therefore, the data model design needs to take into consideration the utilization modes and derived benefits in the perspectives of different stakeholders (Fig. 6).

The primary objective of the *DRF*'s data architecture is to ensure the consistency, availability, usability, safety-critical quality, and democratization of data for AAM operations. In order to accomplish this objective, the data sub-team started with understanding current practices and limitations of data driven systems. The team also initiated the identification of future *DRF* stakeholders and the categorization of them into different groups with different levels of access to the data, decision-making ability, and influence. These findings assisted in drawing logical correlation and operational dependencies among different data elements, thereby, leading to specifying the attributes of a MVBP to showcase the *DRF*.

The design guidelines for the envisioned MVBP's data service models are set as follows:

- The *DRF* Data architecture shall facilitate the availability of actionable and/or decision-making information when it is needed, where it is needed across the data and reasoning fabric for advanced air mobility.
- The *DRF* Data architecture shall ensure high-fidelity, low-latency communication of contextualized data in a highly dynamic and cross-cutting network of advanced air mobility stakeholders.
- The *DRF* Data architecture shall effectively cater and seamlessly adapt to human-to-human, human-to-machine, and machine-to-machine transaction of data and reasoning, optimized via system-wide automation, while preserving the legalistic structure of the advanced air mobility operations.
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Takeaways / Lessons Learned

Key takeaways from the phases I and II data architecture effort are as follows:

- Through contiguous connectivity among the human and non-human data users and distributed processing of data as well as reasonings, DRF will offer a fair and systemic approach to support the diversity in future advanced air mobility operations at scale.
- The DRF marketplace will commercially incentivize the data and reasoning providers to maintain high quality control of the data, thereby enhancing the overall data integrity, efficiency, and trust.
- Striking a balance between taxonomic standardization and semantic interoperability with the data descriptions will make data discovery, transaction, and integration seamless for a wide range of business users.
- Since data in DRF will not be hosted in a centralized repository nor managed by a single entity, DRF will enable privacy-preserving fair data exchange. Data accountability is especially challenging when human and smart machines are involved and the latter work almost autonomously.

H. DRF Reasoning Architecture

To establish a DRF architecture that enables UML-6 operations, we need to consider the reasoning needs of highly automated aircraft operations where the human operator might be supervising many aircraft. The notion of 1:N operations is therefore a central driving factor in arriving at the reasoning architecture. In our approach we identified 1:N operational needs based on an initial analysis of emergency operations in the context of a UML-6 airspace of the future. The general approach consisted of four parts:

1. Developing emergency use case scenarios around 1:N operations with the following needs – (a) surveillance of disaster zones; (b) airborne fire suppression; (c) logistics (transport of people and goods); and (d) airborne support to ground response teams.
2. Establishing the reasoning services categories required to fill the use case needs. The established categories were: (a) Mission planning; (b) Health monitoring; (c) Information Management; and (d) Situational Awareness
3. Definition of reasoning elements and meta data broadly classified based on latencies, computational complexity, and Edge/Cloud/Physical Layer representation.
4. Minimum Viable Product 1:N operations reasoning requirements.

Following this process, we have arrived at four categories of reasoning services:

1. Mission Planning (MP) -- Reasoning for multi-vehicle trajectory generation, with airspace and operational constraints, and distributed contingency management.
2. Health Monitoring (HM) -- Diagnostics and prognostics (constraints and predictions) of systems and components based on data, models and simulations.
3. Information Management (IM) -- Autonomy of model learning from data and physics, with active cross-checking, updating, and validation of uncertainty and performance.
4. Situation Awareness (SA) -- Environmental (terrain, obstacles, no-fly zone, weather) and airspace (vehicle state, planned trajectory, destination) maps, risk assessment

Takeaways / Lessons Learned

For successful DRF reasoning service architecture and integration, there are key technical challenges to be addressed:

- The use case scenarios establish the saliency of the DRF both as an architecture, and as a business proposition that involves multiple stakeholders that should be involved early in the design process.
- Access to edge infrastructure and other technology stacks and capabilities for service migration is a challenge that needs to be addressed early on.
- Automatically learning where best to execute each service (cloud/edge/physical) is important to understand and implement.
- Implementation of a large-scale vehicle simulation capability using a mix of high-fidelity models and simpler kinematic models is important for validation of the DRF architecture.

H. DRF Communications

The Communications sub-team was assembled with individuals having background knowledge in terrestrial communications, aeronautical communications, network security and aeronautics. The approach was to

leverage as much as possible the knowledge and experience gained on other projects where applicable, but to approach the problem in a systematic manner without a pre-conceived solution. Communications results were assembled with relevant knowledge and recommendations, including a number of potential future work activities.

The end to end communications path will consist of a combination of many communication entities, including for example: terrestrial (back haul), terrestrial (local area), air to ground / ground to air, and satellite communications. It is recognized that the link to the aerial vehicle will be the limiting capability link. In addition, it should be recognized that each phase of flight will have different communications requirements. For example, the communications waveform for surface operations will have different requirements than for the airborne link. Similarly, the in-route phase of flight (mostly flat and level flight at high speed and higher altitude) will have different requirements than for terminal area operations (dynamic attitude, changing altitude, maneuvering speeds, approach/landing dynamics).

While performing a survey of the current state of practice in aero communications to support non-payload communications, it is seen that there is a lot of discussion in aeronautical communication related areas. Yet the majority of the efforts are focused on vehicle command and control, or low rate data links, rather than high data rate, non-payload communication links envisioned by the DRF concept which are necessary to support autonomous UML-6 operations. In addition, the efforts appear to be more of “discussion” rather than actual “activity.” There are a number of different efforts, including standards and working groups, which are focused on gaining community acceptance. Still, there is no current community accepted solution and the terrestrial solutions are not necessarily applicable. It is a common myth that “5G will solve it all”, but 5G is only a minimum performance specification and the actual method to meet those specifications are implementation specific.

Currently, there is a lack of definition of data types to support essential non-payload communications for UAM Maturity Level 6 (UML-6). In general, there is a need to survey, identify and classify required communications traffic (data) at a level that is beyond the scope of the DRF efforts. It should be recognized that a key difference between UML-6 and UML4 is the required data flows to support autonomous operations. Once the necessary data types for UML-6 are identified, one can then begin to define the relevant metrics for classifying the link performance:²

- a. **Transaction Time:** The maximum time for the completion of the operational communication transaction after which the initiator should revert to an alternative procedure.
- a. **Continuity:** The probability that an operational communication transaction can be completed within the communication transaction time.
- c. **Availability:** The probability that an operational communication transaction can be initiated when needed.
- d. **Integrity:** The probability that communication transactions are completed within the communication transaction time with undetected error.

Takeaways / Lessons Learned

- Air-to-ground and Ground-to-air communication link will be bandwidth constricted
- There is no current community accepted aeronautical wireless communication solution.
- Terrestrial communications solutions are not necessarily applicable to aeronautical requirements
- Technology being developed to meet terrestrial 5G performance goals is diverging from compatibility with aeronautical usage
- Interference from other users, not link margin, is the limiting factor for aero communications

VI. Conclusion

The Data & Reasoning Fabric (DRF) marketplace will be enabled by an open foundational ecosystem of data and reasoning exchange between the many systems that must seamlessly interact to manage the expected highly complex and dense airspace operations. The DRF opportunity has been assessed and specific recommendations regarding the capabilities of a DRF and its software, data, and reasoning architectures have been developed, along with a potential DRF role for NASA. Highlights of these recommendations are presented here, with details to be provided in subsequent in-depth materials. The MIT Disciplined Entrepreneurship process was used, and proved very useful, in assessing the DRF opportunity and developing the proposed DRF MVBP.

References

- [1] Aulet, B., *Disciplined Entrepreneurship: 24 Steps to a Successful Startup*, John Wiley & Sons, 2013.
- [2] “Manual on Required Communication Performance (RCP) (Draft)”, ICAO Doc. 9869 AN/462 1st ed., 2006