Overview of NASA's Extensible Traffic Management (xTM) Research

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NASA's Unmanned Aircraft Systems (UAS) Traffic Management (UTM) project introduced a new Air Traffic Management (ATM) architecture that utilizes industry's ability to supply industry-developed, third-party services that work complementarily with the FAA-provided Air Traffic Service (ATS) to exchange relevant air vehicle information among the UAS operations and between the UTM and the conventional ATM system. The UTM architecture was used to successfully demonstrate the feasibility of safe, efficient, and scalable small UAS operations in low altitudes below 400 feet above ground level. Following the success and adoption of UTM architecture, the foundational UTM requirements and core properties were generalized to become Extensible Traffic Management (xTM) requirements to support operations of new entrants beyond small UAS, such as operations in high altitudes over 60,000 feet, designated as upper Class E in the United States National Airspace System (NAS). In this paper, the generalization of UTM to xTM and NASA's approach for developing an xTM system for upper Class E Traffic Management (ETM) are discussed. The paper also discusses the planned research to examine the potential xTM-Air Traffic Control (ATC) interactions across multiple xTM systems and identify common coordination procedures, ATC roles/responsibilities, and data exchange requirements. This work is one of the steps for improving interoperability between the xTM systems and ATS, which is critical for safe and efficient sharing of the airspace among the new entrants served by the xTM systems and conventional ATS-serviced operations.

I. Introduction

There is an ongoing need to accommodate new types of aircraft and missions seeking to use the airspace in a non-traditional way. These missions include small Unmanned Aircraft Systems (UAS) performing infrastructure inspections and delivering goods, electric Vertical Takeoff and Landing (eVTOL) vehicles carrying passengers while remotely piloted, and High Altitude Long-Endurance (HALE) aircraft providing communications services loitering in the stratosphere [1-3]. NASA has been performing research and development to meet this need in coordination with the FAA and stakeholder communities, and recently completed the UAS Traffic Management (UTM) project, demonstrating the feasibility of safe, efficient, and scalable operations of small UAS under 400 feet [4]. To enable small UAS operations in the low altitudes where the FAA Air Traffic Service (ATS) is not provided, the UTM project introduced a new Air Traffic Management (ATM) architecture that utilizes industry's ability to supply services under the FAA's regulatory authority. This pioneering ATM architecture is being further developed in NASA's Aeronautics Research Mission Directorate (ARMD) Air Traffic Management-eXploration (ATM-X) project.

The goal of the ATM-X project is to catalyze the airspace community to provide an all-access, safe, and efficient airspace system through innovative solutions [5]. In the project, the UTM requirements and architecture are generalized to become Extensible Traffic Management (xTM) that serve new non-traditional aircraft such as eVTOL and HALE, while preserving the core properties of the UTM architecture such as digital information exchange and

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allowance for third party provided services. With this generalization and preservation, different xTM systems can be developed to support a wide range of new airspace users, also known as new entrants, supporting the FAA's Concept of Operations [6-8]. In this construct, an xTM system must meet all xTM requirements and reflect a distinct characteristic of the operations it supports. For example, the xTM system for upper Class E operations may use third party services for the weather information in the stratosphere, whereas the xTM system for small UAS would use low-altitude weather services. This approach ensures compatibility among different xTM systems at the requirements level and paves a path for improving interoperability between xTM systems and ATS. For example, ATS should be able to deliver tactical functions to xTM operations without considering individual xTM system details when all xTM systems meet the same requirements. This interoperability between the xTM systems and conventional ATS is critical for safe and efficient sharing and management of the airspace among all users [9].

This paper describes the generalization of UTM to xTM requirements and core properties in Section II. Section III introduces NASA's approach for developing an xTM system for a new group of airspace users operating in high altitudes over 60,000 feet. Section IV discusses the planned work to examine the potential xTM-ATC interactions across multiple xTM systems and identify common coordination procedures, ATC roles/responsibilities, and data exchange requirements. Section V summarizes the paper.

II. UTM Generalization to xTM and Core Properties

A new ATM architecture with industry supplied services that complements the FAA ATS was originally invented for enabling safe, efficient, and scalable small UAS operations in low altitudes, named the Unmanned Aircraft Systems Traffic Management in the patent [10]. Since then, the UTM architecture has been adopted globally and recognized as a potential way to provide traffic management services for additional new entrants beyond small UAS [11,12]. The original UTM architecture is shown in Fig. 1 with a brief description of its components below the figure. Figure 2 shows a sequence diagram for operation planning using the architecture.

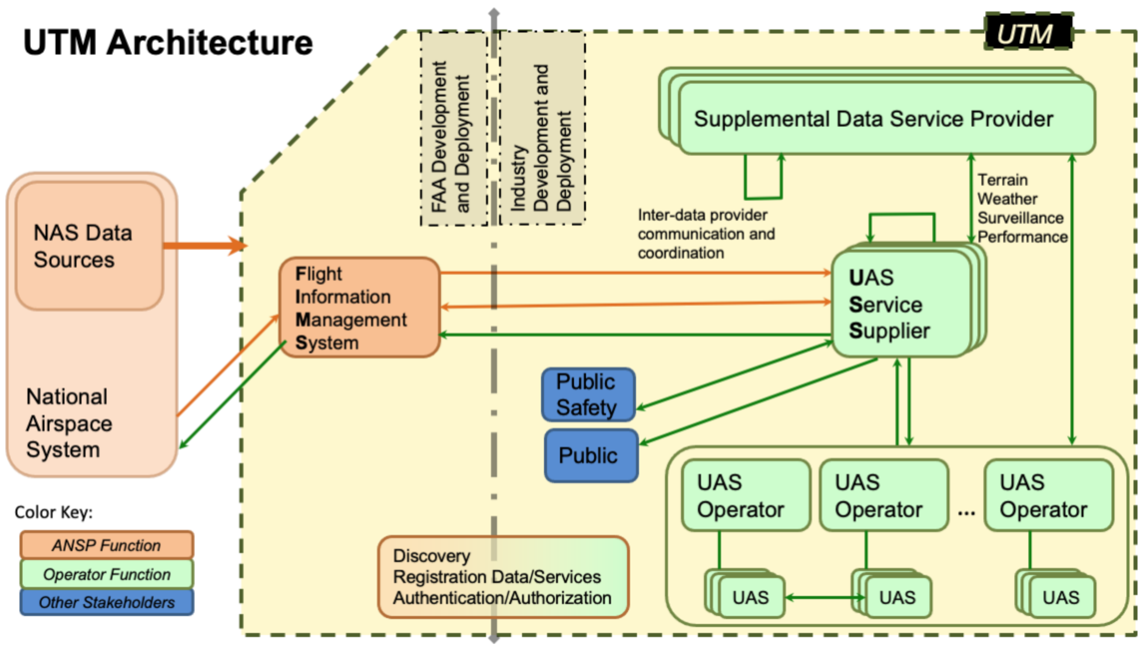

Fig. 1 UTM Architecture

Flight Information Management System, FIMS

FIMS works as a gateway that connects existing ATM infrastructure in the NAS and small UAS operations. FIMS delivers NAS state to the UAS operations, such as constraints and directives, to authorized and registered UAS Service Supplier (USS) so that it can inform the operators it manages. FIMS also receives operational information that can impact the NAS from USS, such as the location of unmanned aircraft that is not under positive control of its operator and delivers it to the NAS.

UAS Service Supplier, USS

USS provides services for UAS operations, such as operation planning where an operation plan is checked against others for conflict. The UTM architecture allows more than one USS to provide service to operators, forming a network to share data for operations that are under their management. Data include intents, updates, requests, position reports, alerts, and other operational messages.

Discovery

Discovery, also known as Discovery and Synchronization Service (DSS), enables USS to find other authentic, registered USSs and facilitate the use of current and consistent data among USSs.

Supplemental Data Service Provider, SDSP

SDSP provides data to support UAS operations, such as terrestrial obstacle locations and description, to USSs and UAS operators. This data is supplemental to data from the NAS.

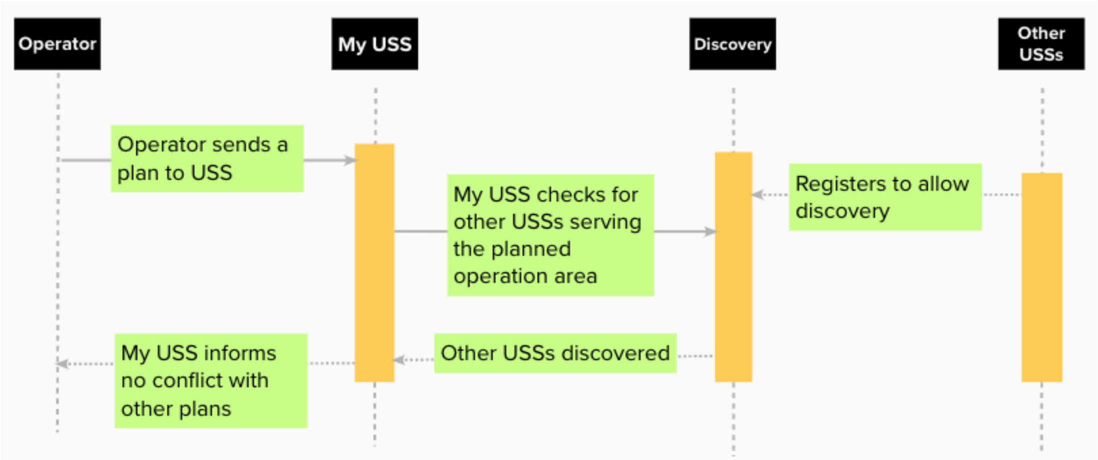

Fig. 1 UTM operations planning sequencing diagram

As the NASA UTM project output and lessons learned were reviewed in the ATM-X project, it became apparent that with generalization, the UTM requirements and architecture are applicable to the management of a wide range of operations involving remotely and/or autonomously piloted aircraft with associated ground systems [13]. For example, one of the UTM requirements, which states that the UTM system shall aid in small UAS staying clear of each other, can be generalized by removing “small”, broadening the definition of UAS to remotely and/or autonomously piloted aircraft with the associated ground system, and replacing the term “UTM” with a more generalized and inclusive term: Extensible Traffic Management (xTM). This generalization was applied to the nine high-level UTM requirements, and the resulting xTM requirements are shown in Table 1 alongside the original UTM requirements.

Table 1 xTM high-level requirements and original UTM requirements

ID	xTM Requirements	Original UTM Requirements
xTM-REQ-01	An xTM System SHALL aid in UAS staying clear of each other	The UTM System SHALL aid in small UAS staying clear of each other
xTM-REQ-02	An xTM System SHALL aid in UAS staying clear of traditional aviation	The UTM System SHALL aid in small UAS staying clear of traditional aviation
xTM-REQ-03	An xTM System SHALL support authentication and identification of UAS	The UTM System SHALL support authentication and identification of small UAS
xTM-REQ-04	An xTM System SHALL provide common situational awareness for stakeholders related to UAS operations	The UTM System SHALL provide common situational awareness for stakeholders related to small UAS operations

xTM-REQ-05	An xTM System SHALL allow for priority of Public Safety operations over other nominal operations	The UTM System SHALL allow for priority of Public Safety operations over other nominal operations
xTM-REQ-06	An xTM System SHALL allow the ANSP to issue directives, constraints, and airspace configurations related to UAS operations	The UTM System SHALL allow the ANSP to issue directives, constraints, and airspace configurations related to small UAS operations
xTM-REQ-07	An xTM System SHALL mitigate the need for ATC to actively control UAS in any airspace	The UTM System SHALL mitigate the need for ATC to actively control small UAS in any airspace
xTM-REQ-08	An xTM System SHALL allow on-demand access of operational data to the ANSP and airspace regulator	The UTM System SHALL allow on-demand access of operational data to the ANSP and airspace regulator
xTM-REQ-09	An xTM System SHALL support UAS from posing a hazard to persons or property on the ground	The UTM System SHALL support small UAS from posing a hazard to persons or property on the ground

Throughout the generalization of the UTM architecture, such as replacing USS with "Service Supplier" and FIMS with "Gateway to the NAS", the six core properties of the UTM architecture were preserved. They are as follows:

A. Native digital exchanges
B. Air-ground integration
C. Allowance for third party services
D. Collaborative airspace management
E. Application Programming Interface (API)-driven, service-oriented architecture
F. Primacy of operator-operator exchanges

A. Native Digital Exchanges

The traditional ATM and ATC environments are effective at maintaining safety and efficiency, but there is friction to any changes in no small part due to legacy systems. These existing systems are not always digital and don't allow for backward-compatible changes. With the opportunity to design a new system, it is important to think digital-first for all information exchanges.

B. Air-ground integration

Aircraft have become more and more advanced with time, reaching a potential inflection point in airspace management due to highly advanced automation, including completely autonomous operations. The allocation of services between airborne and ground systems will vary greatly between domains but ensuring tight integration of those systems including clear delineation of roles and responsibilities will be vital.

C. Emphasis on Third Party Services

The current-day ATM system assumes an authoritative service supplier and a set of operators as the primary actors in the system. Given expected increases in demand for airspace access, it is infeasible to assume that current, monolithic service providers can meet the needs of all operators. There must be a clearly defined role for third party service providers to allow for the growth and scaling of various industries.

D. Collaborative Airspace Management

Between the air navigation service provider (ANSP), the operators, and third party service providers, there needs to be a common understanding of how they all work together to manage the airspace and keep it safe, efficient, and fair.

E. API-Driven, Service-Oriented Architecture

To ensure smooth collaboration, the interfaces between all actors in the system need to be codified into definitive application programming interfaces (APIs). These APIs would be implemented by appropriate actors to provide services within a well-defined architecture. Through careful definition of this architecture, the desired qualities of the airspace can be maintained.

F. Primacy of Operator-Operator Exchanges

In the current ATM system, most communications outward from a given operator are between that operator and the ANSP. Through the architecture definitions and emphasis on collaboration, new, fully digital communication channels among operators (potentially facilitated by third party providers) will be key to gaining efficiencies beyond the current system.

An xTM system for a particular group of airspace users must meet all xTM requirements as shown in Table 1 and be developed to reflect the distinct characteristics of the operations and environment it supports. The next section describes NASA's approach for developing an xTM system for operations in upper Class E airspace and meeting the xTM requirements.

III. Development of an xTM System for Operations in High Altitudes over 60,000 feet

In the United States, the airspace above 60,000 feet, or flight level (FL) 600 is designated as upper Class E. Operations in this airspace are difficult due to challenges associated with flights in low atmospheric density associated with high altitudes. This difficulty has limited operations above FL600 to a small number flown by a specialized military vehicle such as the U-2, which flew without separation provided by ATC using procedures such as Military Authority Assume Responsibility for Separation of Aircraft, MARSA, or restricted airspace [14, 15]. However, recent development in aircraft technology including aerodynamics, energy management, flight automation, propulsion, and structures, led to an increasing number of vehicles that can operate in the low atmospheric density environment. Due to this development and the long endurance capability of some of the vehicles, such as solar-powered flying wings, the number of civil operations in upper Class E airspace is expected to increase [16-18].

Upper Class E is controlled airspace with established separation standards and Instrument Flight Rule (IFR) operations receiving radar separation service if surveillance data is available and non-radar separation service if not. ATS also separates vehicles from special use airspace and provides emergency services when required. However, studies found that the current ATS infrastructure in the NAS may not meet the need of the increasing number of high altitude operations [19-21]. For example, Very High Frequency (VHF) radio communications facilities used by ATS may require an upgrade to serve high altitudes operations, such as transmitter power output increase and frequency engineering to mitigate potential interference from the power increase. Given the time and effort associated with upgrading the ATS infrastructure, NASA and the FAA are exploring an upper Class E Traffic Management (ETM) concept in which operators cooperate with each other using a complementary set of industry-developed services to ATS that supports safe and efficient flight. The operators conducting cooperative operations are responsible for maintaining safe distance from other aircraft and avoiding hazardous conditions such as severe atmospheric conditions and solar events. In the concept, the cooperative operation is voluntary and today's ATS services would remain available to operations above FL600. However, the operator using the ATS service would remain subject to constraints associated with the service, such as the use of non-radar procedural separation due to a lack of surveillance data that may hinder the operation.

Between 2019 and 2020, NASA, FAA, and the high altitude operator community further developed the ETM concept, culminating in the FAA publication of the initial ETM ConOps [3]. Thereafter, NASA proposed to develop an xTM system for ETM in the 1st ETM Workshop, and the consensus supported the development [22]. A draft architecture of an xTM system for ETM that inherits xTM core properties, ETM system in short, is shown in Fig.3. In the figure, ESS is equivalent to USS in the UTM.

NASA is planning to develop the prototype ETM system for an initial evaluation with the ETM community in 2023. The following describes NASA's effort to meet the xTM requirements for the ETM system. The requirements are grouped and the effort to meet them is shown below each group.

xTM-REQ-01 An xTM System SHALL aid in UAS staying clear of each other
xTM-REQ-07 An xTM System SHALL mitigate the need for ATC to actively control UAS in any airspace

To meet these requirements, the ETM system will collect operation plans from the operators so that conflicting plans are identified for deconfliction. A sequence diagram for conflict identification is shown in Fig.4. A flowchart for cooperative resolution of the conflict is shown in Fig. 5 and Cooperative Operating Practice (COP) attributes 1, 2, and 3 in the flowchart are explained below Fig. 5. This conflict identification process and COPs for deconfliction aid UAS to stay clear of each other and mitigate the need for active ATC involvement for UAS control.

xTM-REQ-02 An xTM System SHALL aid in UAS staying clear of traditional aviation
xTM-REQ-03 An xTM System SHALL support authentication and identification of UAS
xTM-REQ-04 An xTM System SHALL provide common situational awareness for stakeholders related to UAS operations

To meet these requirements, a Situational Awareness Service, SAS, will be developed to be a part of the ETM system providing common situational awareness for stakeholders related to UAS operations. The SAS will ingest surveillance data for UAS and traditional aviation so that the operator can have UAS stay clear of the traditional aviation. The SAS will also correlate the surveillance data with UAS unique identification to support authentication and identification of UAS.

xTM-REQ-05 An xTM System SHALL allow for priority of Public Safety operations over other nominal operations
xTM-REQ-09 An xTM System SHALL support UAS from posing a hazard to persons or property on the ground

To meet these requirements, an operation planning service will be developed to be a part of the ETM system and prioritize public safety or equivalent operations over other nominal ones. This service will also consider the ground risk to support the operator from having UAS pose a hazard to persons and property.

xTM-REQ-06 An xTM System SHALL allow the ANSP to issue directives, constraints, and airspace configurations related to UAS
xTM-REQ-08 An xTM System SHALL allow on-demand access of operational data to the ANSP and airspace regulator

To meet these requirements, the ETM system will adopt the UTM methods for allowing the ANSP to issue directives, constraints, and airspace configurations to the operator through ESS via the Gateway to the NAS and allowing on-demand access of operational data to the ANSP and airspace regulator.

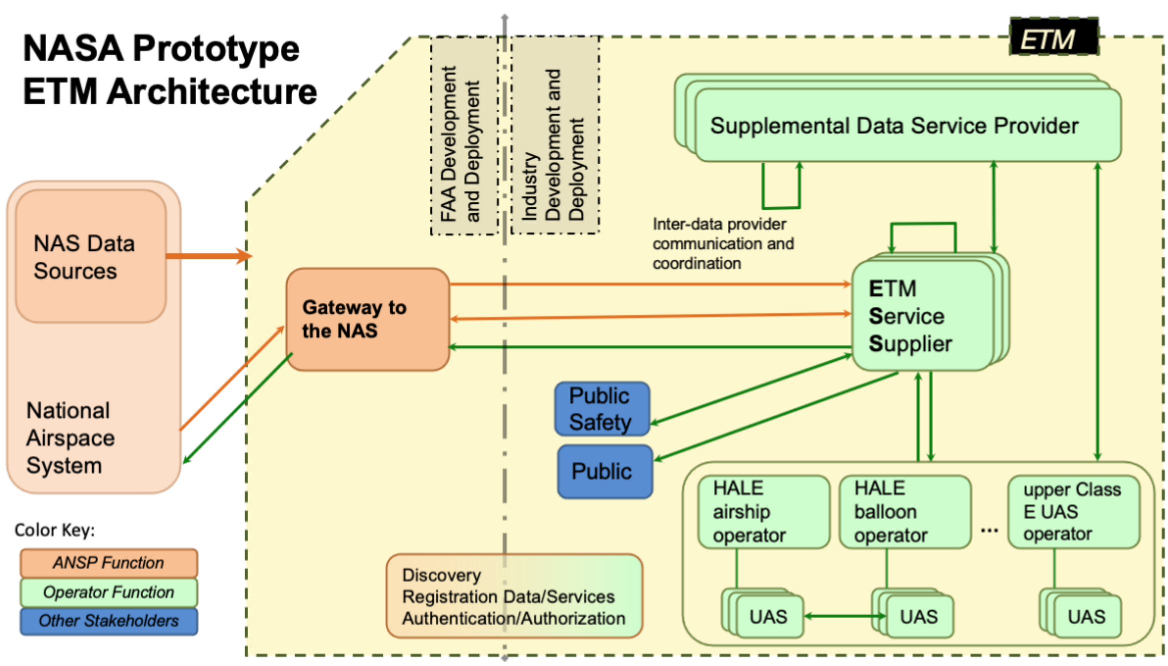

Fig. 3 ETM system architecture

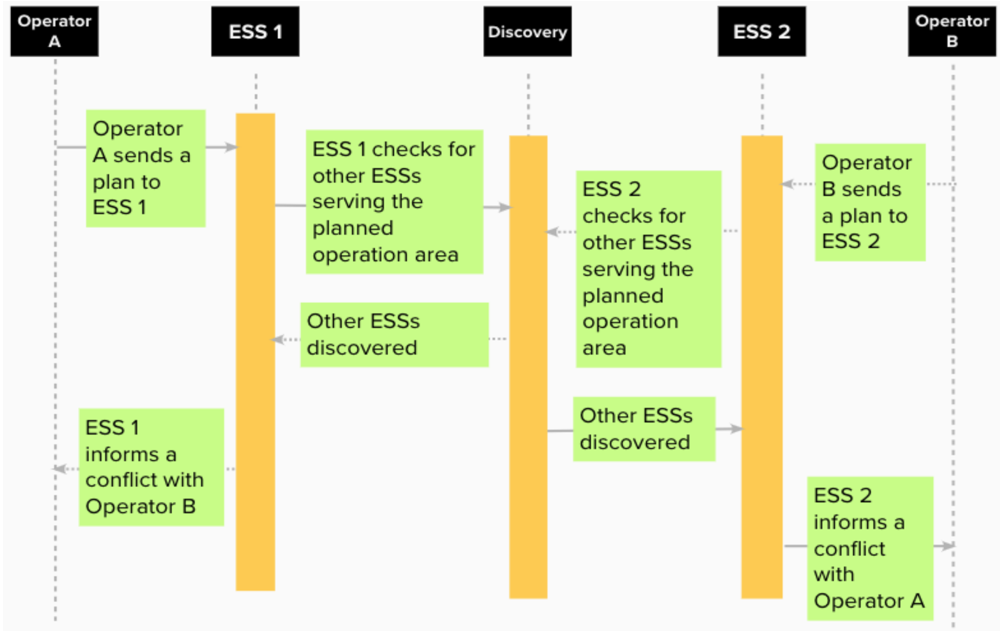

Fig. 2 Operation plan conflict identification in the ETM system

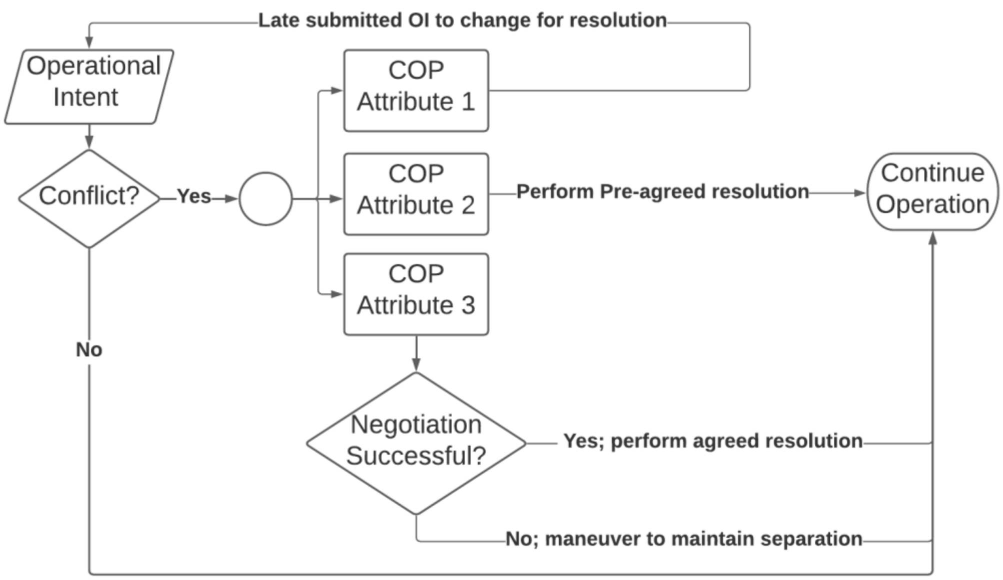

Fig. 3 Operational plan deconfliction through cooperative operating practice

Operational Intent, OI

A volume-based representation of a UAS operation plan, defined in space and time. UAS is expected to stay within the OI at specific confidence level.

COP Attribute 1

First-reserved, first-served rule applies. For example, the operator submitting an OI must modify it to clear conflict with the OIs that are already submitted.

COP Attribute 2
Operators with conflicting OIs have pre-defined agreements to resolve the conflict. For example, the operator of a balloon has an agreement with the operator of fixed-wing HALE to fly higher when their OIs conflict.

COP Attribute 3
Operators with conflicting OIs negotiate to resolve the conflict. For example, the operator of a balloon prefers to remain in the planned altitude and asks the operator of fixed-wing HALE to change the planned heading.

IV. xTM-ATC Interactions

In the FAA's vision for the future of aviation, xTM systems are part of the ATM system, alongside conventional ATS [9]. The different xTM systems are expected to serve different sets of missions and flight profiles with diverse vehicle performance characteristics. In the early implementations of xTM (i.e., UTM, UAM Traffic Management, and ETM), the vehicles are expected to operate in separate, designated airspace that are not occupied by existing traffic, and transit in and out of the conventional ATS environment could be done with limited interactions with existing procedures and tools. However, better integration of diverse xTM operations with conventional air traffic will be needed as the xTM traffic increases in the future, which will allow for more efficient use of airspace with harmonized seamless interaction between current and new entrants, as illustrated in Fig. 6. In a future with more integrated operations and higher xTM traffic density, xTM vehicles will likely need additional advanced coordination support services to handle the complex interactions between a diverse set of vehicles operating within highly overlapping airspace and operations.

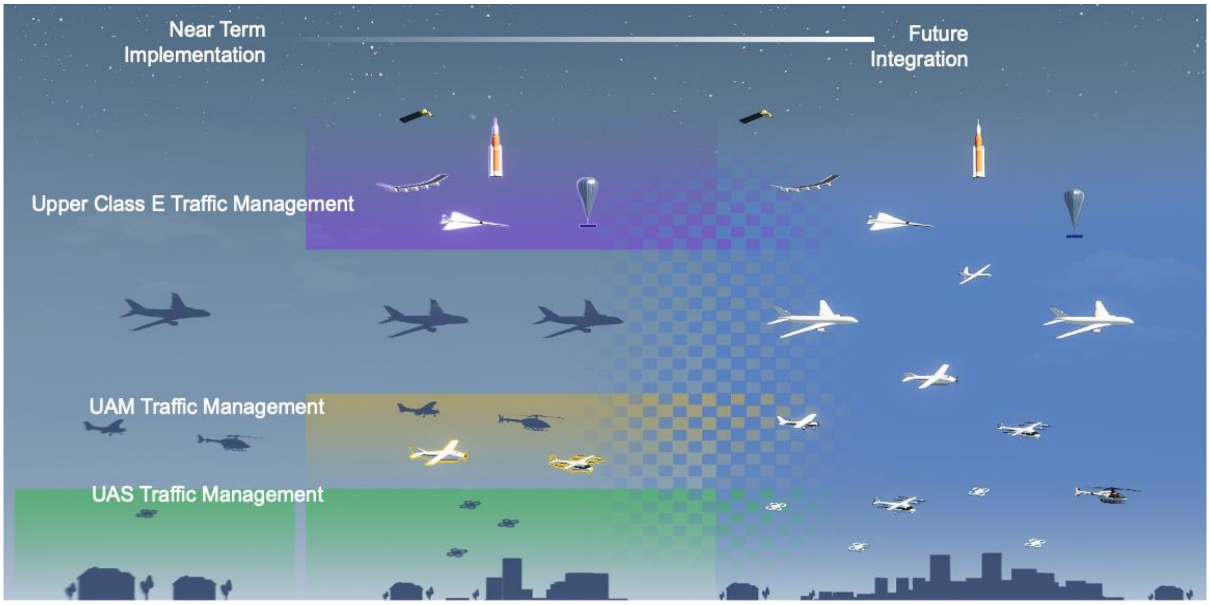

Fig. 4 Integration of xTM and conventional ATS environment

In the early stages of xTM development, xTM operations are expected to operate mainly without ATC supervision. However, on occasions, they are also expected to transit through ATC-managed airspace, sometimes as a part of nominal operations and other times to handle off-nominal / emergency situations. In these situations, there has been a concern that even if all xTM systems meet the same high-level requirements, each xTM system may have its own way of communicating operation intent, vehicle state, other flight plan-related information, and operational procedures. These differences pose significant challenges to the ATC when different xTM systems serviced vehicles enter his/her airspace with different operating goals and practices, in which ATC is expected to provide different types of services and maintain safety within his/her controlled airspace. Therefore, NASA is planning to examine the potential xTM-ATC interactions across multiple xTM systems and identify common coordination procedures, ATC roles/responsibilities, and data exchange requirements across different xTM-ATC interactions that occur under similar trigger events. The overall approach taken is to identify interaction use cases for individual xTM systems first, and then to catalog common procedures and themes across the xTM operations. In particular, UTM-ATC, UAM-ATC, and ETM-ATC interactions are being examined.

An initial set of use cases have been collected from various concept and use case documents across different xTM R&D conducted at NASA, FAA, and other organizations. Additional information about the concepts, potential use cases and other details have been gathered via one-to-one interview / discussion sessions with several xTM researchers.

The results of the use case collection have revealed a common set of scenarios and trigger events across different xTM domains. However, the detailed description of the scenarios, procedures, assumptions, etc. existed unevenly in some domains and not others for any given trigger event / scenario. For example, in situations in which an xTM vehicle needs to enter a sparsely occupied airspace under ATC supervision, one concept such as UTM has implemented an automated airspace authorization method to allow the UTM system and service suppliers to operate in that airspace and relieve most of the ATC's responsibility. However, another concept such as UAM could potentially face a similar situation but the concept or the research have yet to explore ways to implement such a mechanism. Therefore, an examination of the use cases and their corresponding trigger events have allowed us to identify and model missing solutions / coordination mechanisms by translating the procedures from one xTM domain to another.

Once the trigger events have been identified and the associated use cases have been either collected from the literature or developed in-house, they are categorized according to a finite set of trigger events with common themes. The use cases fall under the following broad categories:

- Planned entry into and exit from ATC-managed airspace (with and without intervention needed by the ATC)
- Planned airspace authorization of ATC-managed airspace to full xTM operations and the recovery of that airspace back to ATC management once xTM vehicles leave the airspace
- Unplanned entry into ATC-managed airspace due to off-nominal event with following characteristic differences:
    - Unplanned / off-nominal event but with the flight deck communication and vehicle control intact (e.g., low battery). In this situation, ATC and the flight deck can maneuver the vehicle to safety
    - Unplanned / off-nominal event without C2 (command and control). The vehicle may have a defined lost link procedure or may be a fly-away without a define procedure. In either case, the off-nominal event assumes no direct control of the vehicle.
- Unplanned mass entry of xTM vehicles into ATC-managed airspace
    - Under certain weather event or unplanned airspace constraints along the path of the xTM traffic flow, a closure of that constraint may force an unplanned mass exit of xTM vehicles from xTM operated regions into ATC-managed airspace occupied by non-xTM vehicles.
- Non-xTM vehicles entry into xTM airspace
    - Numerous xTM concepts allow non-xTM vehicles to transit through xTM system operated regions. In some of those cases, ATC is expected to provide support for these non-xTM vehicles during transit. Different xTM concepts make slightly different assumptions about the ATC's role, which may result in different coordination procedures and services for similar trigger events.

The next step in the xTM-ATC interactions research is to develop a common set of coordination procedures for each category of trigger events across the xTM domains. An initial goal is to be able to find a common set of procedures across the different types of xTM vehicles that can translate into a common set of data exchange requirements to support the procedures. The ultimate goal is to expand on these procedures to identify, develop, and demonstrate a new set of coordination services that can support multiple xTM operations in highly integrated, high traffic scenarios.

V. Summary

The novel UTM architecture that utilizes industry's ability to supply services for complementing ATS was successfully used to demonstrate the feasibility of safe, efficient, and scalable small UAS operations in low altitudes. The foundational UTM requirements and core properties are generalized to xTM requirements to support operations of new entrants beyond small UAS. The generalized xTM requirements will be met as NASA develops an xTM system for ETM (i.e., the ETM system). NASA is planning to develop a prototype ETM system for an initial evaluation with the ETM community in 2023.

NASA is also planning to examine the potential xTM-ATC interactions across multiple xTM systems and identify common procedures, ATC roles/responsibilities, and data exchange requirements across different xTM-ATC interactions under similar scenarios and trigger events. This work is one of the steps for improving the interoperability between the xTM systems and ATS and a development of new coordination services for future integrated operations. The examination of xTM-ATC interactions and the development of coordination services is critical to achieve scalable, safe, and efficient operations that seamlessly co-exist with traditional vehicles in highly integrated future air traffic operations.

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