Cooperative Upper Class E Airspace: Concept of Operations and Simulation Development for Operational Feasibility Assessment

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Upper Class E Traffic Management (ETM) is a novel community-based traffic management concept incorporating the FAA, NASA, and industry's collaborative efforts to support safe, efficient, and scalable future operations in the airspace near and above 60,000 ft. The concept complements Air Traffic Control (ATC) infrastructure and Air Traffic Management (ATM) services by facilitating cooperative operations with ETM provided services. This paper presents an initial Cooperative Separation Management (CSM) concept for High Altitude Long Endurance (HALE) vehicles' conflict detection and resolution during their extended operations. A prototype simulation platform has been developed to visualize and assess the concept during demonstrations to stakeholders. Further development plans for simulations and the CSM concept are discussed.

Nomenclature

ADS-B	=	Automatic Dependent Surveillance-Broadcast
ADS-C	=	Automatic Dependent Surveillance-Contract
ANSP	=	Air Navigation Service Provider
ATC	=	Air Traffic Control
ATM	=	Air Traffic Management
CSM	=	Cooperative Separation Management
ConOps	=	Concept of Operations
ETM	=	Upper Class E Traffic Management
FAA	=	Federal Aviation Administration
FIR	=	Flight Information Region
HALE	=	High Altitude Long Endurance
LOA	=	Letters of Agreement
NAS	=	National Airspace System
NASA	=	National Aeronautics and Space Administration
RTT	=	Research Transition Team
SST	=	Supersonic transport
UTM	=	Unmanned Aircraft Systems (UAS) Traffic Management

I. Introduction

Upper Class E Traffic Management, ETM, is a novel community-based, cooperative traffic management concept, where operators hold responsibility of coordinating, executing, and managing operations within a regulatory framework [1]. The ETM concept enables vehicles to safely enter upper Class E airspace (above 60,000 feet or FL600). Current National Airspace (NAS) infrastructure and ATM services provide limited/or no air traffic

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management services to support civil aircraft operations in such airspace. The FAA has published separation standards for both surveillance (radar) and procedural (non-radar) separation for operations in the ETM environment, but these standards are mostly applicable to only military operations. Some vehicles in the United States are operating without provision of direct separation service by the ATC (e.g., Military Authority Assumes Responsibility for Separation of Aircraft [MARSA]) [1].

Hence, the ETM Concept of Operations (ConOps) v1.0 [1] was developed by the FAA, documenting the vision for ETM based on discussions between the FAA, NASA and the industry stakeholders. NASA and the FAA formed a Research Transition Team (RTT), consisting of subject matter experts, psychologists, researchers, and engineers with extensive experience of conducting research in the aerospace/aviation domain. The team will work closely together to mature the cooperative traffic management concept for upper Class E airspace by identifying architectures, functionalities, data exchange protocols, and operational requirements to enable safe, secure, efficient, and scalable ETM operations. This joint effort on the concept development is currently being pursued, informed by ETM stakeholders such as high-altitude balloon and High Altitude Long Endurance (HALE) vehicle operators.

In the ETM environment, Cooperative Separation Management (CSM) operations are intended to take place with minimal air navigation service provider (ANSP) involvement to minimize the burden. This can be achieved by facilitating shared situation awareness among operators with ETM services, ensuring safe and efficient operations. The FAA's authority and responsibility over the airspace does not change with the introduction of ETM services.

The initial CSM concept is developed, which focuses on solving potential in-flight conflicts between HALE unmanned fixed-wing vehicles and balloons. The HALE vehicles, either currently operational or soon-to-be deployed, can be airborne for an extended length of time (e.g., up to 6 ~ 12 months).

This paper is organized as follows. Section II discusses the general background of ETM and its challenges. Section III presents the approach that is taken to rapidly enable new ETM vehicles for safe operations in the upper Class E airspace. Section IV will discuss the scope of initial concept development activities. Section V will present the CSM concept, encompassing primary actors and their roles and responsibilities. Also, the set of functionalities that are being developed to ensure safe separation management will be illustrated in this section. Section VI will describe the simulation capability that will be used to prototype the concept for demonstration and assessment of operational feasibility. Finally, next step plans, conclusions, and acknowledgements will be discussed in section VII, VIII, and IX respectively.

II. Upper Class E traffic management

The ETM environment is defined as operations around and above FL600. A wide range of vehicles are expected to access this airspace frequently (see figure 1) due to new vehicle development such as unmanned aircraft, and new technologies such as airframe, solar power, and electric propulsion technology [1].

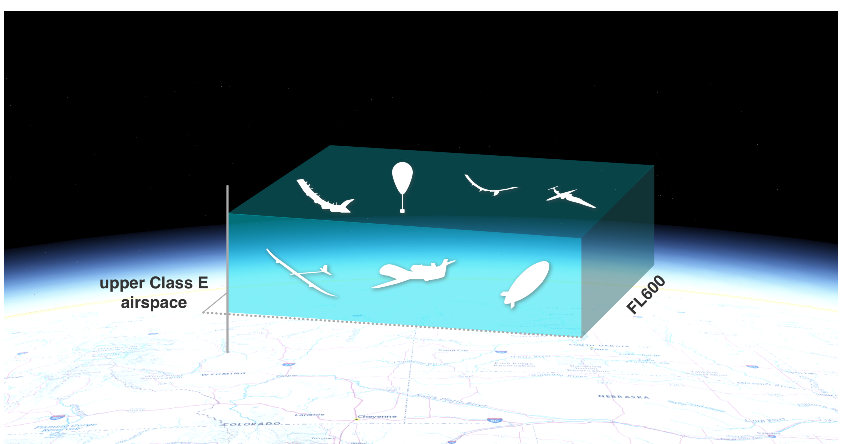

Figure 1. Notional ETM operations with vehicles including HALE unmanned fixed-wing, unmanned free balloon (HALE & short endurance), SST/subsonic, high speed unmanned fixed-wing airplane, and HALE airship

A variety of vehicle types are expected to be operating in the ETM environment in the near future. These include: (a) Supersonic transport (SST) carrying passengers, (b) HALE unmanned fixed-wing vehicles, (c) HALE balloons, (d) high-speed unmanned fixed-wing airplanes, and (e) HALE airships. Beyond the enumerated vehicle types, upper Class E airspace will be accessed by space launches and sub-orbital spaceflight operations, mostly transiting through the airspace, and even hypersonic vehicles in the future. Each vehicle type will be operating with a wide range of performance characteristics, which varies by time of day, and ranges from prolonged moving or stationary vehicles, to extremely fast-moving vehicles. There are various operating missions—e.g., constellation, point to point, and transitional operations. There is a wide variance in duration of operations as well (from hours to months). All these factors impose unique challenges for the traffic management concept development.

Table 1 summarizes the general characteristics of five different vehicle types, including the potential ones, operating in the ETM environment.

Table 1. General characteristics of the potential ETM vehicle types

Vehicle type	Mission	Desired Notional Flight Level	Notional Cruise Speed	Notional gross Weight (lbs)	Notional Mission Duration time
Supersonic/Subsonic	Transport passengers	FL410 - FL600+	Mach 1.1 - 3	133,000 - 170,000	3 - 5 hours
HALE unmanned fixed wing	Military operations, surveillance missions, scientific research, communication service	FL500+	12 - 40 knots (true speed, wind dependent)	117 ~ 1,500	14 days - months
Unmanned free balloon (HALE & Short Endurance)	Communication service, scientific research	FL500 - FL650	8 - 15 knots (up to 100 knots, depending on winds)	~ 165	Months
High speed unmanned fixed wing	Military operations, surveillance missions, scientific research	FL500+	Mach 0.6	26,700	30+ hours
HALE airship	Communication service, scientific research	FL640 - FL650	8 knots (up to 100 knots, depending on winds)	~ 12,500	Months

Although the demand for accessing upper Class E airspace by civil aircraft is projected to increase substantially, the existing NAS infrastructure and services are limited in the ability to cost-effectively accommodate such projected demand [1]. Hence, NASA and the FAA are collaborating with industry partners to develop a traffic management concept for upper Class E airspace to provide requirements for operations, core ETM service functionalities, and a pathway to handle projected traffic density.

The following five aspects were considered during the ETM concept development process:

1. Scalability of the ETM systems enables various vehicle types and diverse missions (commercial, public/government, and research). Scalability also accommodates additional expansion or functionalities to the ETM systems. The ETM system should be scalable to handle projected traffic increase in upper Class E operations. The system should also be scalable for managing operations across multiple Flight Information Regions (FIRs) and global application.
2. Safety of the airspace operations needs to be ensured. ETM operations should impose no additional risk to the current conventional ATM environment. Also, it should meet the targeted safety level set by the FAA. The safety level is designed to ensure safety of people and property, but also to ensure safe separation and capacity-demand balancing.
3. Efficiency of airspace utilization needs to be achieved. Introduction of ETM vehicles should not disrupt current NAS operations. Furthermore, ETM should maintain or enhance ETM operations' efficiency, while maintaining the maximum efficiency of individual operations.
4. Fair access to airspace must be assured among all ETM operators. The projected ETM traffic increase will cause more airspace competition. Some ETM operators may compete to loiter over the same location for revenue generation (e.g., communication service). Thus, equitable airspace management is critical for granting fairness among the ETM operators.
5. Security of the ETM system must be maintained. The ETM operators should satisfy FAA-stipulated data archiving and sharing requirements to ensure protection against intentional and unintentional acts against people and/or property.

Early-stage ETM concept development will mainly focus on cooperative operations emphasizing safety. Meanwhile an initial scalable ETM architecture with services is established as a component of the mature operational

ETM system. ETM operations could lead to fatal accidents, where no other aspects outweigh cost of human lives and also the current traffic in the upper Class E airspace is very low. Other aspects will be considered, once: 1) understanding of the operations is achieved with sufficiently aggregated operations data, 2) more operational requirements are standardized and agreed among the participants of the ETM operations, and 3) the effectively operational ETM ecosystem architecture is constructed with efficient communication flow (e.g., with construction of digital data exchange protocols).

III. Research Approach

The initial ETM concept development will focus on allowing the current and new entrants vehicles to safely operate within the upper Class E airspace, where provision of ATM services is currently limited. The associated challenges to the concept were identified by stakeholders and researchers through meetings and discussion. Their involvement was critical to validate the characteristics of the problems, understand needs, and make assumptions during concept development. Moreover, their input played an essential role in determining whether our concept development work is operationally satisfactory and feasible from all potential ETM participants' perspectives.

The inputs from the industry partners are integrated with lessons learned from the past research work on exploration of various ideas in air traffic management concepts. This encompasses investigation on distributed air-ground traffic management concept [2], separation assurance function allocation among pilot, air traffic controller and automation [3], commercial supersonic transport operations [4], as well as the recent research work on the development of Unmanned Aircraft Systems (UAS) Traffic Management (UTM) Concept [5].

The concept development research will continue to engage the industry partners and collaborate with the FAA closely throughout the development process, while leveraging a rich body of the past air traffic management research.

The approach will consist of the following general steps:

1) Gathering concerns and interests from the stakeholders
2) Performing concept development research to address the needs and define requirements
3) Designing functionalities, roles and responsibilities of involved actors, and procedures for enabling the concept
4) Prototyping to test feasibility and incorporate input from the stakeholders to improve

The above process from 1) to 4) will be iterative to continuously refine the concept.

IV. Initial Scope of the Concept Development and Assumptions

The initial research scope aims to address the immediate stakeholders' interest of operational concept development for inflight CSM, focusing on operations of the HALE vehicles—i.e., specifically looking at HALE unmanned fixed-wing aircraft and balloons in the upper Class E airspace above FL600 first. These vehicles are currently operational or at the ready-to-be-deployed stage in the near future.

A multilayer vehicle deconfliction approach could be taken to ensure a safe ETM operational environment. The approach could consist of two layers: 1) pre-departure deconfliction, and 2) inflight cooperative separation. Pre-departure deconfliction is performed before launch to preemptively resolve or mitigate potential conflicts with other vehicles and avoid airspace constraints, e.g., no-fly zones, weather, and obstacles, at each vehicle operating stage. In the conventional ATM environment, this serves to regulate potential demand and capacity imbalance problems. The initial ETM concept of operations assumes that the pre-departure, and transit to and from the ETM environment, will be managed within the existing separation concepts where ATC is responsible for providing separation services [1]. The HALE operators are obliged to comply with regulations. Currently, HALE unmanned fixed-wing vehicles submit flight plans and file Notice to Airmen (NOTAMs) and are authorized with letters of agreement (LOAs) before launch. HALE balloon operators do not submit the conventional flight plan to the ATC due to trajectory uncertainty. Instead, they provide notification to ATC and other operators sharing the airspace. These vehicles have limited maneuverability and are susceptible to wind. Hence, ATC may take a conservative approach by segregating them from other traffic in various airspaces during the transit phase utilizing segregated airspace and special use airspace. Additionally, HALE vehicles are expected to launch/descend from/to remote locations or low volume airports during nighttime to minimize interactions with other vehicles, reducing ATC's workload [1].

Collision avoidance is commonly considered the last resort to prevent a mid-air collision, which could be added as the potential third layer in addition to pre-departure deconfliction and inflight CSM. However, it requires a real-time ground-based or onboard capability to accurately monitor vehicles based on position broadcast and trajectory prediction to detect conflict. The efficient communication mechanisms between the vehicle operators need to be established as well. Moreover, it entails performance-based temporal and spatial separation criteria. The FAA and NASA are currently investigating the separation criteria requirements. Such information could provide the protection bubble accounting for uncertainties [6].

The FAA has published several white papers describing emerging and existing Communication, Navigation, Surveillance (CNS) capabilities which are applicable to the ETM environment [7, 8, 9, 10, 11]. However, some HALE vehicles are not yet fully equipped with the required technologies. For example, some HALE vehicles lack redundant satellite navigation systems to reliably provide their position, ensuring safe temporal and spatial separation distance. Some may use a less accurate altimeter. Moreover, ETM vehicles may be equipped with Automatic Dependent Surveillance–Broadcast (ADS-B), but this surveillance mechanism is known to provide limited oceanic surveillance. Automatic Dependent Surveillance–Contract (ADS-C) could serve as a feasible solution to provide surveillance in oceanic and remote continental regions. However, ADS-C is not suitable for tactical separation due to high latency and limited update rate [7].

Most HALE vehicles have limited capability to apply tactical maneuvers to maintain separation. For instance, the HALE balloon has limited ability to control speeds and headings as it relies on prevailing winds to control its movement. Its maneuverability is limited to altitude change only. Some vehicles are light, which makes them vulnerable to wake turbulence and wind. Furthermore, HALE vehicles are mostly remotely piloted unmanned vehicles. Some are controlled by artificial intelligence-based autonomous navigation that evaluates and executes course modification without having much human involvement. This new way of controlling unmanned vehicles may pose unexpected barriers that are yet to be discovered.

The initial concept development will be based on the available technological capabilities and standards, where currently, there are some limitations as mentioned above. Hence, a conservative and risk-averse approach will be taken to ensure this last layer of deconfliction function is unlikely to be reached, as providing proper tactical deconfliction at this last layer may be infeasible.

The next section will discuss the second layer of deconfliction—inflight CSM—in more detail.

V. Inflight CSM

Inflight CSM in the ETM environment is similar to the inflight separation services provided by the ANSP in the conventional ATM environment although the CSM may involve a look-ahead time for conflict identification that is longer than ones typically used by ATC. However, separation services are to be predominantly performed by operators in the ETM environment with minimal/or no involvement of ANSP. It should be noted that this approach to airspace management, while cooperative in nature, will operate under the FAA's regulatory and operational authority.

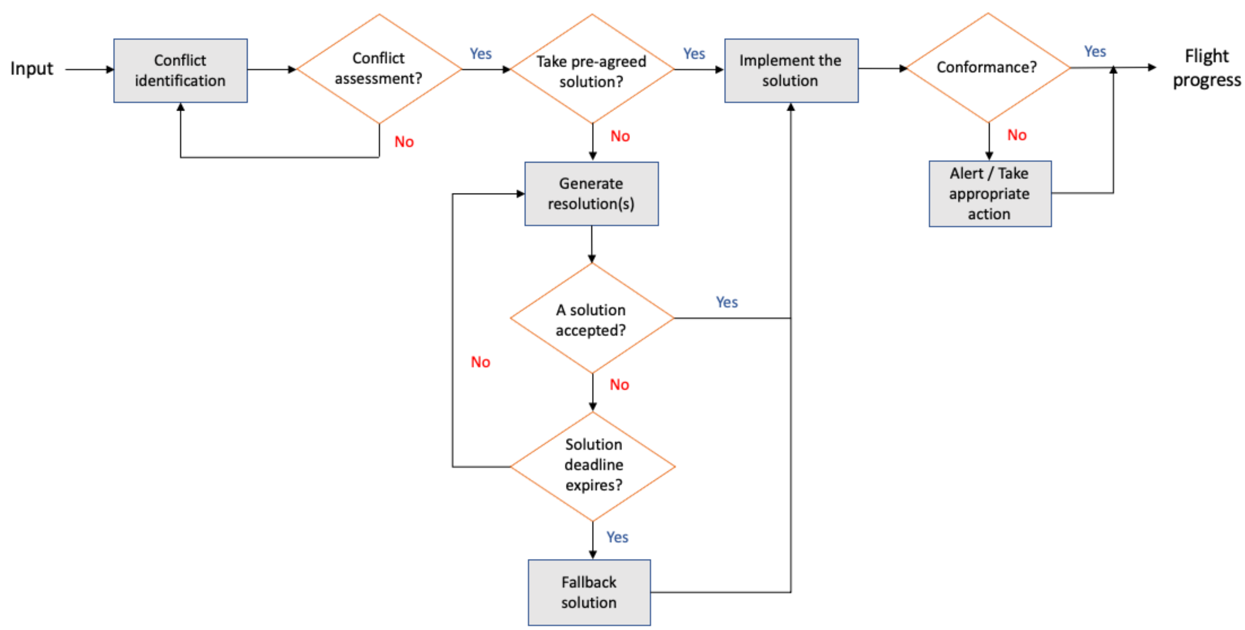

Figure 2: inflight CSM flow model for operations above FL600

Figure 2 presents the inflight CSM process. The flow diagram shows a multi-stage conflict detection, assessment, resolution, implementation, and conformance monitoring process. The collision risk is assessed by estimating hazard severity and likelihood of occurrence [12]. If the risk exceeds a threshold level, a resolution should be executed by either taking a pre-agreed solution or utilizing any operator's negotiation protocol until the solution deadline expires.

In the following sections, the inflight CSM operation participants are identified, and their initial roles, responsibilities, and functionalities are described.

A. Primary actors of the ETM's inflight CSM

The potential actors, their roles/and responsibilities of the inflight CSM operations are determined based upon discussions and presentation materials with industry partners and the FAA. The ETM concept development leverages UTM's conceptual elements such as services [5]. The inflight CSM operations are mainly performed by two actors, ETM services supplier (ESS) and ETM operator. The FAA will serve as an ANSP and a regulator overseeing all operations, including upper Class E airspace [1].

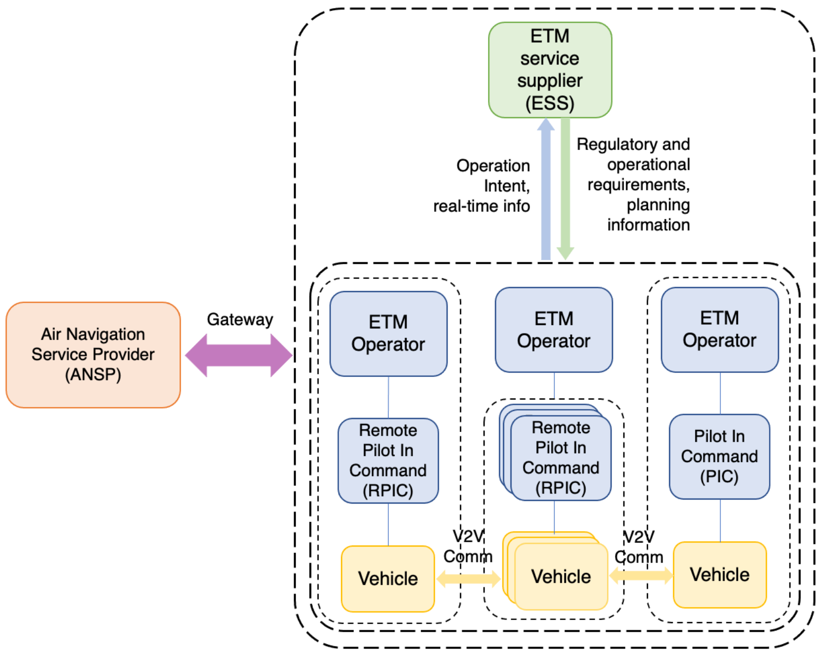

Figure 3. Notional representation of potential interaction between the ANSP, ESS, ETM operators

Figure 3 illustrates the interaction among the ANSP, ESS, and the ETM operator. A gateway performing a function similar to UTM Flight Information Management System (FIMS) [5] is expected to connect ESS and the NAS/ANSP. The block diagram is flexible to adopt new concepts, and scalable to involve multiple ESSs providing services in a federated manner similar to UTM UAS Service Suppliers (USSs) [5]. The block diagram could serve as a component in the operational ETM ecosystem in a mature stage. In this paper, the initial scope assumes a single ESS in the NAS.

The ESS could be operated by ETM operators, commercial, or government entities. In the context of the inflight CSM, the ESS primarily offers support for safe airspace operations. The ESS could also serve as a communication bridge among ETM operators by information sharing. For example, the ESS can share flight intent to promote safe operations without disclosing any confidential information. Furthermore, the ESS could support the operators with operation planning, vehicle de-confliction, conformance monitoring, and support the operators to meet regulatory and operational requirements. ESS could also support archiving operations data in historical databases.

ETM operators are expected to provide a description of the mission, such as launching and landing, contingency plans, overall flight profile and flight intent in the context of future vehicle positions expressed in the 4-D profile. They also need to provide telemetry or the state of the operation updates to other ETM operators via ESS to foster shared situation awareness among all the participants in the cooperative separation management environment. There should be collective agreement on accuracy, frequency, reliability, and continuity of the telemetry or the state of the operation reporting about safety assurance in the ETM operations. ETM operators are responsible for managing their operations by meeting regulatory responsibilities, plan flight/operations, and safely conduct operations utilizing all available information [1].

ATC may utilize the ETM operation data to service vehicles transiting to and from upper Class E airspace via the controlled airspace, which is a research area that NASA is currently investigating to support effective facilitation of such activity. Flight plans submitted to ATC in current day operations may be inadequate to support long duration missions (i.e., limited to 24-hours), which may need some modifications to allow frequent re-filing or possibly flight plan stitching. Flight plans consisting of latitude and longitude coordinates may produce potential impacts on the ATC system, requiring some changes. Some ETM vehicles are susceptible to weather and may replan take-off time and vehicle trajectories frequently. Fluid and flexible communications among the actors are imperative. Hence, the interface between ANSP and ESS or ETM operators is illustrated in figure 3, where details in the data exchange protocols are not included in this paper.

The next sections describe the initial set of inflight CSM functionalities identified to support the ESS and ETM operator, including:

1) Share - Flight intent attributes shared by operators
2) Detect - A conflict detection capability based on the flight intents sharing
3) Evaluate - An approach to evaluate the conflict severity in terms of risk
4) Revise - A capability to revise the flight intent and share conflict-free path using a standardized data exchange protocol
5) Monitor - A conformance monitoring functionality to conform whether ETM vehicles comply with the revised flight intent

B. Flight intent generation for HALE unmanned fixed wing aircraft and balloon

Successful inflight cooperative separation management requires the ETM operator's intent to be shared to others via ESS. However, ETM vehicles' distinct operational characteristics (e.g., airspeed, maneuverability, and weight) and mission duration pose unique challenges for flight intent generation. This section describes the flight intent generation capability for HALE balloon and unmanned fixed-wing aircraft.

Unlike conventional aircraft performing point-to-point operations, HALE vehicles may remain stationary or loiter in a pattern and operate for an extended duration (up to months). In addition, HALE operators may not have high-confidence flight intents that capture end-to-end operations. As a result, they may frequently replan during operations. Hence, performing deconfliction based on using a first-reserved first-served approach prior to take-off is unsuitable for HALE operations particularly from a scalability standpoint. Such an approach may only be applicable for short-duration flights. Therefore, the HALE operators propose a "rolling-window" concept for the intent sharing mechanism [10]. The rolling window concept enables HALE vehicles to operate for a long duration and serve a wide range of areas with flexibility to replan frequently.

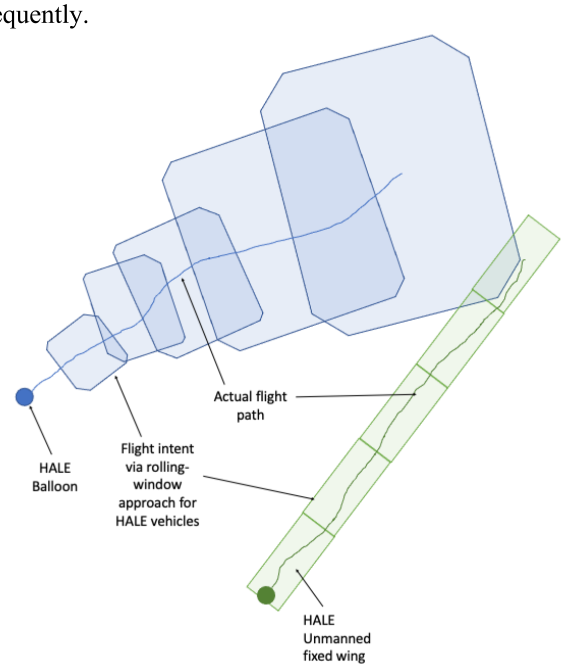

Figure 4: A generic illustration of the rolling-window approach with a HALE balloon and a HALE unmanned fixed-wing through flight intent sharing

Figure 4 depicts the rolling-window approach by a HALE balloon operator and a HALE unmanned fixed-wing operator through flight intent sharing. The HALE operators may share a serial flight intent represented in polygons. The flight intents are segmented in *M* minutes (referred to as "flight intent update interval" in this paper) over *n*-hour operations. In the figure, polygons represent the estimated future position's boundaries with 99% confidence at each M-minute segment [13]. Research and development with operator input is needed to either define *M* and *n* values or leave them dynamic. These values could impact airspace usage efficiency and induce inequality issues. Also, flight intent may be replanned frequently due to limited vehicle controllability. Their light weight could be impacted by the wind [13].

Although both HALE balloon and HALE unmanned fixed-wing aircraft could take the same rolling-window approach for flight intent sharing, the flight intent's characteristics may differ. The HALE balloon has a distinctive performance characteristic of limited or no capability to control the trajectory once it launches [14]. Advanced balloon systems can control altitude by adjusting the shape of the canopy or venting lifting gas, but the surrounding winds mainly dictate the balloon's lateral movement. Wind prediction data contains errors from several sources—i.e., resolution errors because of sampling, measurement error due to instrument specification, temporal error caused by temporal interpolation. The wind data errors make prediction of a balloon's precise trajectory a challenging task [15].

A probabilistic approach for the HALE balloon's flight intent generation has been proposed by the industry partners. The flight intent polygon contains all possible future positions, growing over prediction time due to uncertainty. The HALE balloon operator may dynamically replan and share the revised flight intent as frequently as once per minute [13]. A subsequent research will be conducted to define optimal flight intent update rate. The probabilistic approach is strictly tied to continuous change in wind speed and direction.

By comparison, the HALE unmanned fixed-wing aircraft has more controllability than the HALE balloon. Hence, the HALE unmanned fixed-wing aircraft may share flight intent like conventional fixed-wing aircraft flight plans consisting of a sequence of waypoints. However, the HALE unmanned fixed-wing vehicles are still susceptible to performance limits. The wind in the stratosphere could be stronger than the vehicle's maximum speed. The lightweight vehicles are vulnerable to environmental disturbances [1]. The solar power-based HALE vehicle's maneuverability may vary with time of the day. The vehicles may have less power during the evening [13]. Therefore, the flight intent is shared by a 4-D polygon along their intended path. The HALE fixed-wing vehicle with more controllability may require significantly smaller polygons than the HALE balloon [13].

C. Conflict detection and assessment

The ETM ecosystem intends to achieve an equal or better target level of safety (TLS) than the conventional ATM system, as severe and catastrophic events could lead to direct loss of human occupants on board. Even if most ETM operations can be performed by unmanned vehicles, collisions may still produce secondary hazards such as vehicle debris falling on vehicles flying underneath or objects on the ground that could lead to fatal injuries. The actual level of safety (ALS) in conventional ATM is measured by the actual number of accidents per operation. The ALS fatal en route accident risk from 1959 – 2006 is 1.40×10^{-8} per flight hour [16].

Collision risk prediction could be an element that is incorporated into the schema as part of the deconfliction process of the ESS. In this scheme, the ESS is responsible for notifying the ETM operators immediately when the predicted collision risk exceeds the pre-determined threshold. The initial ESS concept assumes that vehicles will move along shared flight intents generated either by a probabilistic approach or a sequence of waypoints enclosed by polygon. A conflict is detected when the intersection between any pair of flight intents is identified both temporally and spatially. The conflict detection's lookahead time could be determined with the HALE operators' mutual agreement considering the minimum required time to take maneuvers with a sufficient protection buffer to ensure safety.

There is ongoing investigation regarding computation of the conflict likelihood, which could lead to better understanding about managing risk in the ETM environment [17]. The collision's likelihood is a controllable variable, which is inversely related to the efficiency of the operations. Further investigation should carefully assess the overall risk imposed by the ETM operations to meet the TLS while introducing more efficiency into ETM operations.

D. Conflict resolution methods and deconflict strategies

In the presence of a conflict, the ESS would be responsible for notifying ETM operators. Once an ETM operator receives the notification, they would choose to either execute a pre-agreed resolution or use an operator-preferred negotiation protocol to develop the final resolution action. Such a collaborative resolution process would need to be completed before the solution deadline.

Figure 5 shows the notional timeline for the deconfliction process. The baseline concept is a first-reserved-first-served (FRFS) as an initial step in the conflict resolution process with a right-of-way rule-based method. For example, the later submitted operational intent is subjected to change to avoid conflict with the earlier submitted ones, and vehicles with high maneuverability yield to vehicles with low maneuverability. The industry partners, in collaboration with NASA and FAA, are working together on developing consensus on the appropriate right-of-way rules and cooperative operating practices. This type of rule-based method is considered the standard conflict resolution protocol due to its efficiency and simplicity [18]. The industry partners are developing emergency and priority operations as well as the standard protocol for resolution, which will be incorporated in following work.

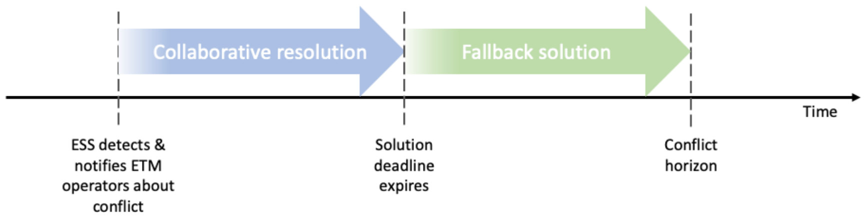

Figure 5: Notional conflict resolution timeline

A drawback to the rule-based conflict resolution approach is that it may lack flexibility [18]. This can be addressed by allowing the ETM operators to negotiate different resolution strategies based on their business models. This process could be executed in a more manual manner initially. In the future, however, such a process could be assisted by automation capabilities and efficient data exchange protocols facilitated by the ESSs and/or supporting services based on industry partners' and stakeholder inputs.

Inflight deconflict strategies can be grouped into three categories: (1) adjusting speed, (2) adjusting heading or turn rate, and (3) adjusting altitude. However, some HALE vehicles have limited maneuverability to adjust and maintain position reliably. The initial concept assumes that the HALE balloon can only change altitudes with significantly large lateral uncertainties. The HALE unmanned fixed-wing vehicle is assumed to be capable of executing all three deconflict strategies, but it may still require a sufficiently large protection buffer due to its limited maneuverability. The operators can choose different deconflict strategies such as moving away from the predicted conflict point or maneuvering the vehicle into hover state until the deconflict is completed.

When the collaborative resolution phase is not executed by the minimum required time to take maneuvers by either party, a fallback emergency solution can be implemented. For example, an emergency solution could set the high maneuverability vehicle to yield to the low maneuverability vehicle.

E. Conformance Monitoring

The ESS could serve as a conformance monitor to ensure ETM operators follow the agreed upon resolution plan. The ESS can alert the operators when the vehicles are not conforming to their resolution plans, or not executing the plans by the deadline. The ESS may also advise the ETM operators to execute an emergency resolution protocol. An example of a vehicle non-conformance situation that may occur is a HALE vehicle deviating off course due to being susceptible to wind. The HALE vehicle may not be able to take a resolution action properly with strong wind conditions relative to the vehicle speed. Figure 6 shows winds in the upper Class E airspace on 0Z/05/17/2021. The winds in the airspace are generally mild but there are occasions where the winds could be stronger than the maximum speed of the HALE vehicle.

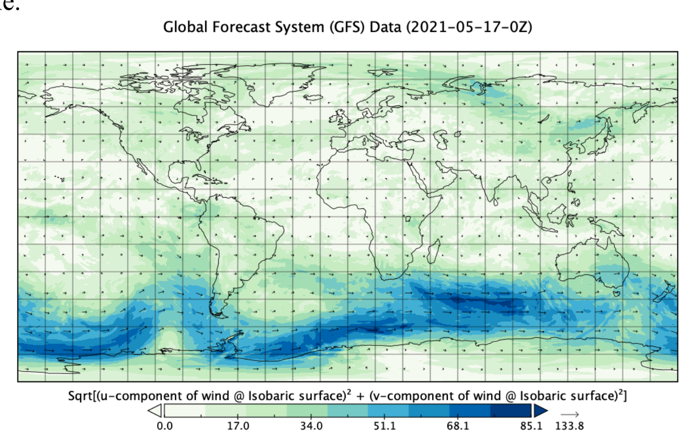

Figure 6: Winds in the Stratosphere (2021-05-17- 0Z) at around 61400 ft (7000 pa)

The capability to monitor or predict non-conformance/off-nominal situation is currently being investigated to proactively prevent undesirable situation from happening.

An experimental proximity monitoring function has been developed for the ESS to ensure safe operations by monitoring the temporal and spatial distance between the ETM vehicles. This module notifies the ESS when the distance between a pair of vehicles exceeds the minimum required temporal and spatial threshold with sufficient buffer to take resolution maneuvers. The proximity monitoring function will run independently from conflict detection. It allows the ESS and the ETM operators to maintain good situation awareness and mitigate undesirable situations ahead of conflict detection. The module's logic is based on a commonly practiced mitigation strategy used by air traffic controllers to handle complex airspace in conventional ATM [19]. This experimental proximity monitoring tool is introduced as an additional safety net to account for sudden flight intent change and non-conformance/off-nominal situations. Further research and development will be conducted with community input for its functionality.

VI. Simulation Development

A new ETM simulation capability called ETMAutoSIM is being developed by NASA to serve:

1) Proof-of-concept of the flight intent sharing and inflight CSM functionalities for operational feasibility verification and validation
2) Provision of interactive demonstrations for stakeholders to visualize the rolling-windows approach concept and collaboratively refine the concept
3) Delivery of research insight and software subsystems as an integral part of the ETM ecosystem accessible by NASA and its partners to facilitate research and software development

The ETMAutoSIM follows a similar software design to a proven tool: TMIAutoSIM [20]. The TMIAutoSIM is a real-time and fast-time Traffic Management Initiative (TMI) concept evaluation tool developed for conventional air traffic management. The following sections describe the ETMAutoSIM simulation architecture and the key attributes, functionality description, and ongoing simulation development plans.

A. ETMAutoSIM simulation architecture and key attributes

The ETMAutoSIM simulation capability was developed to conduct rapid concepts and procedures to assess their operational feasibility. Figure 7 depicts the notional architecture of ETMAutoSIM.

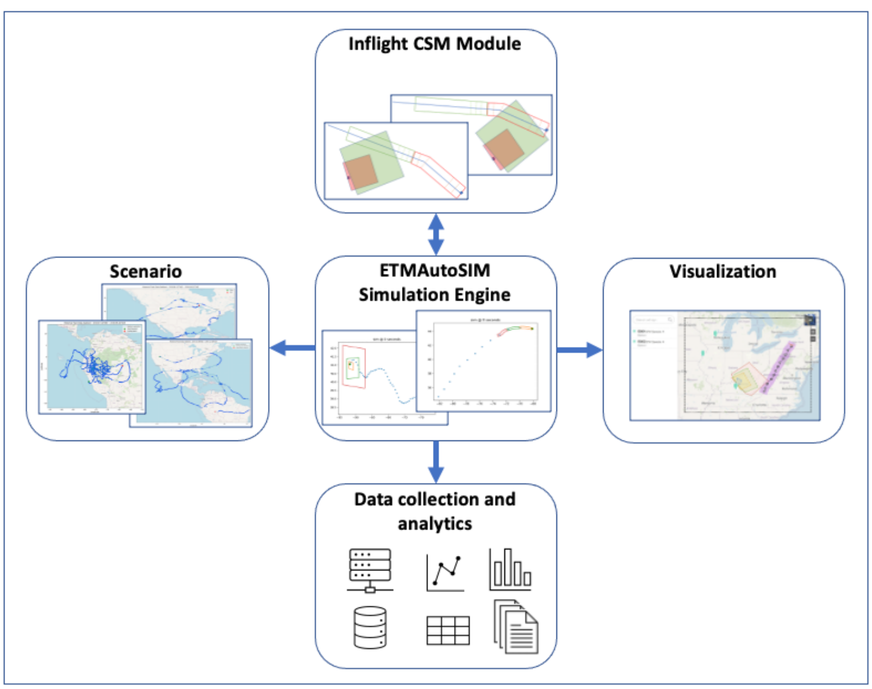

Figure 7: Notional ETMAutoSIM simulation architecture

Some key attributes of each module that have been implemented are described below:

1) Scenario: several customized scenarios were created to test and validate the ETM concepts with HALE fixed-wing vehicles and balloons. These scenarios are loaded into the simulation engine to mimic the actual operations information shared among the ETM operators and ESS at a user-specified update rate.
2) Simulation engine: this uses the rolling-window approach to generate each vehicle's flight intent, which is represented in a set of polygons.
3) Inflight CSM: a preliminary inflight conflict detection logic is implemented by detecting overlapping flight intent polygons at the same temporal instance with user-specified intent lookahead time and flight intent update interval.
4) Visualization: visualization tools will be utilized for testing ETM vehicle operations and functionalities in both real-time and fast-time simulation mode.
5) Data collection and analytics: all data from the simulation process are logged for both real-time analysis and post-simulation analysis

New functions and new modules can be rapidly and flexibly added to the simulation architecture based on the stakeholder's input. Furthermore, the ETMAutoSIM is planned to be integrated into the overall ETM ecosystem to emulate potential ETM operations for evaluation and demonstration.

B. ETMAutoSIM Initial Implementation

This section will present the core functionalities implemented in the ETMAutoSIM simulation environment in more detail.

Intent generation capability for the HALE balloon

The probabilistic approach is preferred by HALE balloon operators for flight intent generation [13]. Hence, a Monte Carlo simulation method is developed to mimic the HALE balloon's flight intent represented in a set of polygons. The Monte Carlo method first uses the historical wind data statistics, initial heading, and balloon speed [21] to predict all possible vehicle trajectories within a user-specified intent lookahead time and update interval. The flight intent polygon is then calculated as the minimum convex polygon containing all predicted track points. Figure 8 shows a flight intent example generated by running a 10,000-time Monte Carlo simulation.

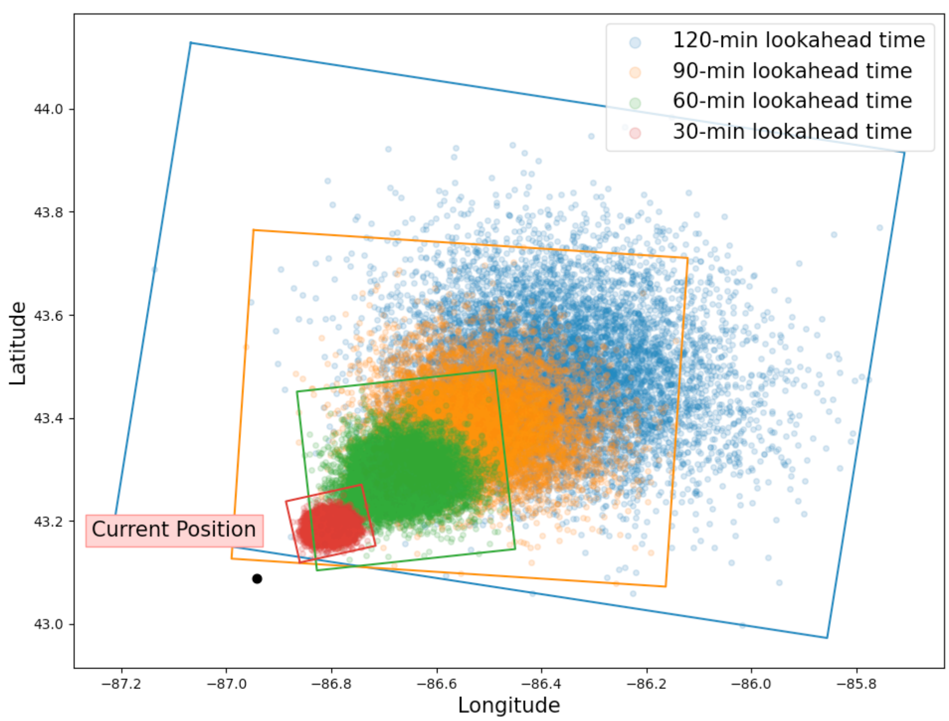

Figure 8: a HALE balloon flight intent example generated by a Monte Carlo method in the ETMAutoSIM (red: 30-min lookahead time, green: 60-min lookahead time, orang: 90-min lookahead time, blue: 120-min lookahead time)

The flight intent is shared for the next 120-minutes (n) from the current position (indicated by the black dot at longitude -86.942 and latitude 43.088), which is segmented by a 30-minute flight intent update interval (M). In the figure, the colored dots represent all the possible positions at different lookahead times (e.g., 30, 60, 90, and 120 minutes) bounded by the polygons. The balloon flies at 8.8 m/s toward 45 degrees from North. The quadrilateral polygon shape was chosen for computational consideration, which can be altered to closely approximate any complex shape that the stakeholders would like to practice. In the simulation, the flight intent is generated at every telemetry position update using the best available wind data provided in the scenario file. The short-term wind forecast for the region can substantially digress from the actual wind measure [22]. Hence, the scenario files are created based on the historical balloon track data, which contains the wind field that the balloon experienced per minute at various altitudes, providing the most accurate estimate of the wind field [22].

The HALE balloon operator should also share the vertical protection buffer as part of the flight intent. The vertical buffer size can depend on various factors, such as the performance characteristics of the balloon for holding the altitudes stably, the accuracy of the altimeter, and the navigation system it uses. The vertical separation requirements are to be further discussed and investigated.

Intent generation capability for the HALE unmanned fixed wing aircraft

The HALE unmanned fixed-wing aircraft has more controllability than balloons, but it is still challenging to adhere closely to its planned path because of its limited propulsion performance and light weight. Hence, a buffer boundary is defined around the planned flight path shared by the operators. Figure 9 shows a notional HALE fixed-wing aircraft flight intent

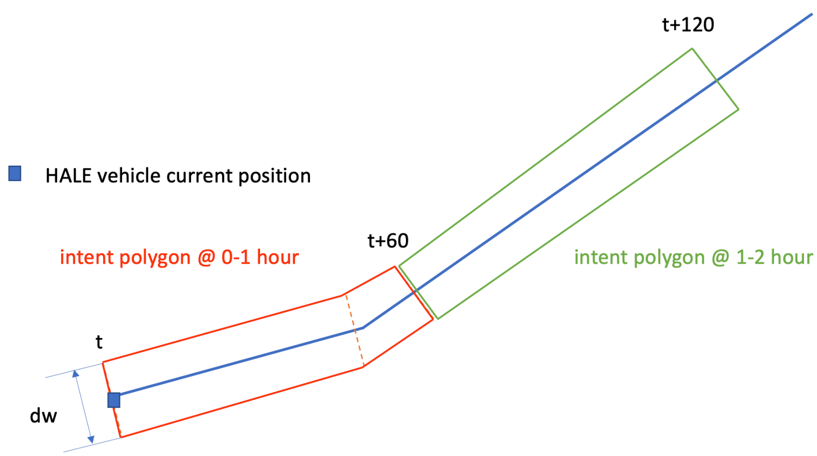

Figure 9: notional flight intent of the HALE unamends fixed wing aircraft

In the figure above, the HALE fixed-wing aircraft flight intent is represented in polygons at a one-hour update interval (M) with a two-hour look ahead time. The red polygon represents the flight intent polygon at the next zero to 60 minutes. The green polygon represents the flight intent polygon at the next 60 to 120 minutes. The polygon vertices are created perpendicular to the flight heading. The maximum lateral deviation dw is determined by the vehicle performance provided by the operators. The operator can share and update the flight intent to other operators at a specific rate (e.g., 30 minutes). In summary, the fight intent polygon's width and height are mainly determined by the vehicle performance to follow the planned flight path. The flight intent polygon's length is mainly determined by the vehicle speed.

Figure 10 shows a 2-D HALE fixed-wing aircraft flight intent example for the next 12 hours of operations (n) from the current position indicated by a black dot (longitude = -68.127, latitude = 44.352). The vehicle is expected to fly at 40 knots. The lateral buffer is indicated as dw, which is set as 25 miles. The full path is broken down into 60-minute flight intent update intervals (M). The flight intent update interval (M) can be adjusted to be the same between different vehicles when applying the conflict detection logic.

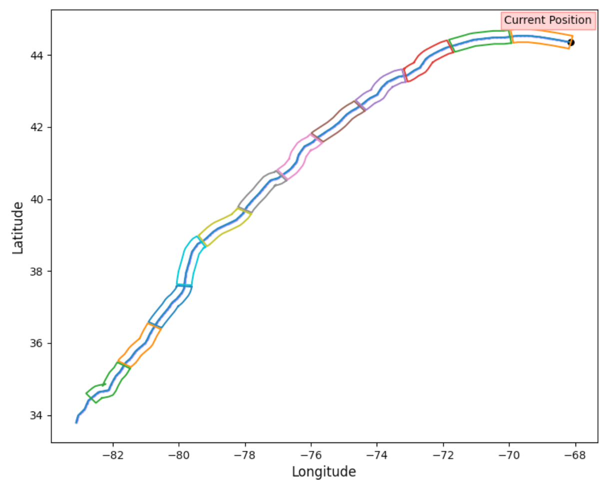

Figure 10: a HALE unmanned fixed wing flight intent generation example in the ETMAutoSIM

C. Conflict detection logic for the inflight cooperative separation management

Preliminary conflict detection logic has been developed by detecting overlap between any pair of HALE balloon and HALE fixed-wing flight intent polygons during the same flight intent update interval (*M*) identified at a specified lookahead time. The specific size of the flight intent update interval (*M*) and minimum look-ahead time value need to be agreed upon by the operators to ensure sufficient time to resolve conflict.

Figure 11 illustrates how the conflict detection logic performs to identify conflict between a HALE balloon and a HALE fixed-wing aircraft. The figure shows the flight intents of both vehicles for the next two-hours of operations (n = two hours), which are segmented by one-hour flight intent update interval (M = one hour). The two-hour lookahead time is pre-agreed as the minimum required time to resolve conflict for the purposes of this simulation.

In the following figure, the red polygon represents a flight intent polygon at the next zero to one hour. The green polygon represents a flight intent polygon at the next one to two hours. In case one, a conflict between the HALE balloon and the HALE fixed-wing aircraft is detected as there is an overlap between the same green flight intent polygons. In case two, conflicts are detected as both green and red flight intent polygons are intersecting. In case three, no conflict is detected because intersection occurs, but it is happening at two different flight intent lookahead times.

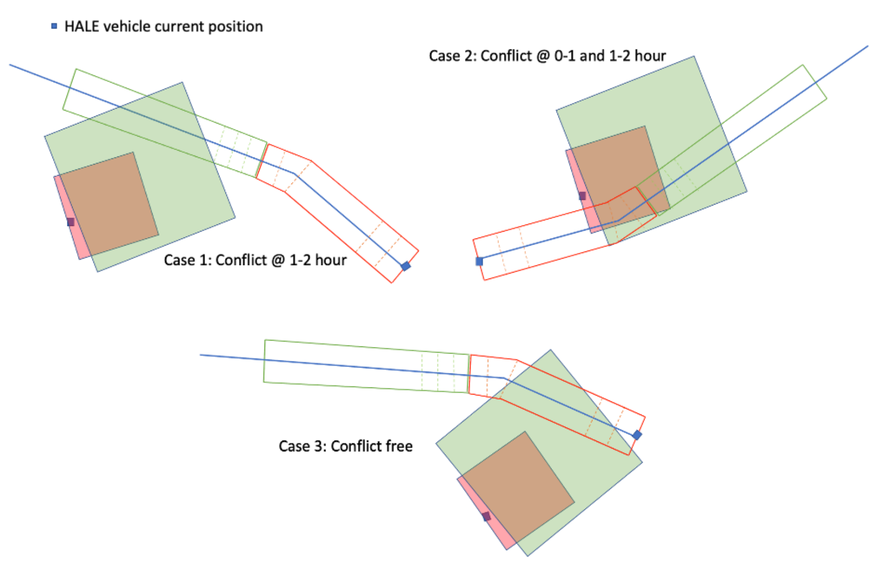

Figure 11. Illustration of inflight conflict detection logic between a HALE balloon and a HALE unmanned fixed-wing aircraft using three cases. The colored polygon represents flight intent at zero to one (red) and one to two hour (green), respectively

Finally, figure 12 presents several snapshots from a full 60-hour simulation run to test out the conflict detection logic. The figure shows the case where a HALE balloon and a HALE unmanned fixed-wing aircraft are interacting. At every telemetry update (i.e., set at 30 minutes), both operators share flight intent for the next three-hours of operations (n = three hours), which are segmented by a 60-minute flight intent update rate (M). At 7200 seconds into the simulation run, a conflict is detected at the three-hour lookahead time, indicated by the same-colored polygons overlapping.

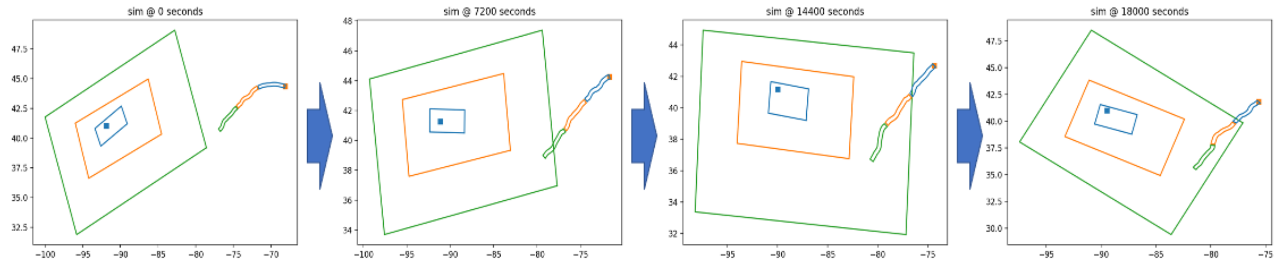

Figure 12. Snapshots from a full ETMAutoSIM simulation run at different time instance (0, 7200, 14400, and 18000 seconds) to assess the conflict detection logic

D. Human integrated systems research preparation

The ETMAutoSIM is designed to serve multiple purposes, including: (1) provision of an interactive demonstration for stakeholders to visualize the ESS functionalities, and (2) evaluating the operational human-systems interfaces and data exchange protocols and procedures.

Figure 13 depicts the schematic view of the overall demonstration platform that is under development. The demonstration platform integrates the functionalities discussed in the previous sections with real-time visualization capabilities using UNITY engine [23] and Bokeh library [24].

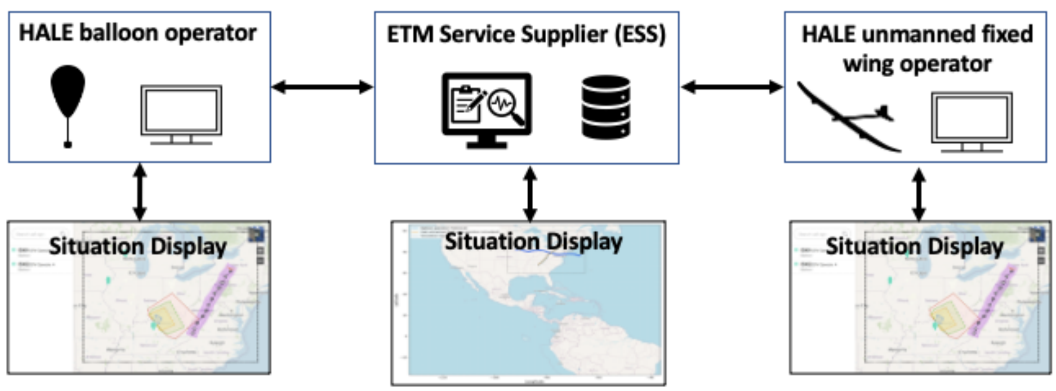

Figure 13: Schematic view of the simulation infrastructure

The functionalities of the ETMAutoSIM serve as a subsystem of the overall ETM ecosystem infrastructure. The operators share flight intent and operations data via data exchange protocol. The 4-D flight intent data format and data contents will be standardized through continuous discussion with the stakeholders. Use case scenarios will be developed for demonstration as well as evaluation of user interfaces with tools that support ETM and ESS operators.

VII. Future plans

The NASA team will work collaboratively with the FAA and industry partners to mature the ETM concept. New concepts, procedures, and functionalities will be rapidly prototyped, visualized and validated in the ETMAutoSIM simulation environment. Other ETM vehicle types such as supersonic transport, airship, and high speed unmanned fixed wing aircraft will be gradually explored and tested using the ETMAutoSIM capabilities.

VIII. Conclusion

This paper developed an initial inflight CSM concept for ETM. The concept aims to enable safe operations of HALE unmanned fixed-wing aircraft and HALE balloons. The primary actors and their roles and responsibilities have been identified. An initial set of functionalities are identified and implemented with a new simulation tool called ETMAutoSIM. The description of the simulation capabilities and the plan for extending the capabilities for further human/system simulation research is presented. Some preliminary results are also presented.

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