A Framework for Dynamic Architecture and Functional Allocations for Increasing Airspace Autonomy

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To enable scalability of air travel for use cases such as cargo delivery, it is anticipated that future air traffic operations will involve unmanned aircraft operated by remote pilots. Of particular interest are schemes where a small number of pilots operate a large number of vehicles, mitigating high cost and pilot shortage issues. Such architectures require increased levels of automation and supervisory control modes. They also require ensuring safe operations when the command and control link to the vehicle is degraded or lost completely, rendering the vehicle autonomous. To evaluate these variable and dynamic architectures, this paper will present a framework for decomposing the functions necessary to ensure safe, orderly, and expeditious air travel, assessing the agents in the system, and classifying the levels of autonomy. Then, an example allocation to agents of roles for the function of separation assurance is presented, highlighting the dependency of the allocation on three main factors: time criticality of a potential separation violation, the ratio of pilots to vehicles, and the loss of the command and control link.

I. Nomenclature

ASP = Airspace Service Provider
ATC = Air Traffic Control
ATCo = Air Traffic Controller
AUT = ASP Automation
C2 = Command and Control
CNS = Communications, Navigation, and Surveillance
DAA = Detect and Avoid
ERAM = En Route Automation Modernization
GS = Ground Station
HARS = High Altitude Relay System
IISA = Information Acquisition, Impact Assessment, Solution Planning, and Action Implementation
LC2L = Lost C2 Link
m = Number of Remote Pilots
N = Number of Unmanned Aircraft
NAS = National Airspace System
NASA = National Aeronautics and Space Administration

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RLOS = Radio Line-of-Sight
RP = Remote Pilot
UA = Unmanned Aircraft
UAM = Urban Air Mobility
UAS = Unmanned Aircraft System
UTM = UAS Traffic Management
VFR = Visual Flight Rules

II. Introduction

It is anticipated that unmanned aircraft, operated by remote pilots, will be introduced into the National Airspace System (NAS) in the coming years. Of particular interest, especially for remotely piloted cargo operations, are schemes where a small number of pilots operate a large number of aircraft. These schemes, referred to as m:N operations, where m remote pilots (RP) operate N unmanned aircraft (UA), may help to mitigate the high cost of operations and the ongoing pilot shortage. However, for such m:N operations to be feasible, they must be highly scalable. Highly scalable operations will require increased levels of automation and supervisory control modes. In addition to safe, orderly, and expeditious operations while m:N operations are occurring, remotely piloted aircraft present a unique challenge: they operate via a command and control (C2) link system, which can become degraded or even severed. In this lost C2 link (LC2L) state, the RP cannot send controls to the UA, meaning that, by necessity, the vehicle must be able to safely operate in the NAS by itself.

Regardless of how these aircraft are being operated, the overarching goal of safe, orderly, expeditious, and secure flow of air traffic must be maintained. The abstract tasks, such as separation assurance, that must be executed to satisfy this goal are called functions. These functions are nominally allocated along roles and responsibilities (e.g., the function of separation assurance is satisfied by the role of the human pilot, who has a responsibility to “see and avoid” traffic). However, to enable m:N operations and provide for safe operations in LC2L conditions, new allocations of the roles and responsibilities among humans and automation will be necessary. These humans and automation, especially new automation that perform independently and are yet to be employed, are agents – entities or actors capable of executing a function. There are numerous ways in which functions can be allocated amongst the agents, and these ways can be influenced by a variety of factors. The framework presented in this paper is intended to help determine what functions and how these functions should allocated to agents, including automation, to enable scalable m:N operations under nominal conditions and safe operation under LC2L conditions. Additionally, because aircraft operations are a dynamic process (e.g., the context in which the plane is flying changes frequently through the phases of flight), the framework must be capable of supporting dynamic function allocation. That is, the allocation process must be flexible enough to be applied in several different, and changing, operational contexts.

The framework itself is presented in Section III. The framework is built upon previous complexity literature [1-5] and will leverage and expand upon this previous work to decompose functions necessary for safe, orderly, and expeditious flight using a cognitive model, breaking down the function into four steps. Next, the agents in the system who can execute functions are discussed. These agents, including automation, fall along two axes of autonomy: the level of automation (i.e., from fully human controlled to fully machine controlled) and the control locus (i.e., how distributed the control is, from a central agent to distributed edge agents – those agents separate from and nominally controlled by the central agent). These axes will be discussed, as will the operational context. The operational context includes the endogenous – internal and inherent to the function – complexity and difficulty of the functions as well as the complexity and difficulty that arises from exogenous – external to the function – considerations, such as class of airspace.

The system in which agents operate is called the architecture. In Section IV, we expound further on the architecture and agents and factors which impact them. The physical and human aspects of the communication, navigation, and surveillance architecture, the operator-vehicle architecture, the airspace and airspace services architecture, and the impact these aspects can have on the functional allocation process are discussed.

In Section V, we present an example functional allocation process, using the separation assurance function. This example will focus on three primary dependencies which will impact the allocation process: time criticality, m:N operations, and LC2L conditions. Another paper [6] will provide a more in-depth conflict and collision avoidance example using this framework and functional allocation process.

III. Autonomy Framework

The autonomy framework proposed in this paper is an extension to the one proposed in Idris *et al.* for increasing airspace autonomy from an air traffic management perspective [3]. Namely, Idris *et al.* focused on increasing autonomy of air traffic management functions regardless of the underlying architecture of the airspace structure or the operator agents. The framework is extended in this paper to capture how the function allocation process is dependent upon the architectural elements – especially the physical infrastructure – of the airspace system. The framework is also extended to capture the effects of the operational context on the function allocation process. The main elements of the framework in Idris *et al.* are described in this section with some extensions, while the reader is referred to the original paper for more details. The framework consists of the following main components: (1) functional decomposition, (2) agents, (3) operational levels of autonomy, and (4) operational context as exogenous factors of autonomy.

A. Functional decomposition

Regardless of how an aircraft is operated, there are overarching goals that must be achieved to ensure safe, orderly, expeditious, and secure flow of air traffic. Abstract tasks that must be satisfied to achieve these overarching goals are called functions. Functions are nominally allocated along roles and responsibilities (e.g., a pilot on board "seeing and avoiding" other traffic). Following Idris *et al*., we abstract functions such that they could theoretically be achieved by any agent. The motivation is that an autonomous agent, such as an Unmanned Aircraft System (UAS), may achieve these objectives using somewhat different functions and methods than a centralized agent (e.g., an airspace service provider dictating to the UAS what to do to achieve safe, orderly, and expeditious operations). Other functional abstractions and decompositions were reported in the literature, such as Feary *et al*. [7]. In this paper, we do not provide a detailed functional decomposition for airspace operations; we refer the reader to these other publications for more details. Instead, we use separation assurance as an example function to demonstrate the use of the framework for functional allocation that is dependent on different agent architectures and operational contexts. In current operations, separation assurance is a function that is shared between air traffic controllers and pilots. However, with remote pilots, the pilot is no longer on board to fulfil the "see and avoid" portion of the separation assurance function. To systematically assess the allocation solution space, we abstract the function to its fundamental goal – assuring separation – and decompose it.

The functional decomposition is performed to break down the abstract function into finer components that match human cognitive models or other similar breakdowns. Following Idris *et al.*, a function in this paper is decomposed into a typical cognitive model consisting of four steps colloquially termed IISA:

1. **Information acquisition (I):** Acquiring the information needed for performing the function. For example, for separation assurance, the information includes the states and intents of the ownship and intruder vehicles in addition to any qualifying information related to the performance and capabilities of the vehicles involved.
2. **Impact assessment (I):** Assessing the information to identify any problems and their impacts. For example, for separation assurance, a potential conflict is predicted with an assessment of its uncertainty, severity, and time criticality, among other relevant metrics.
3. **Solution planning (S):** Planning solutions to mitigate the problems and their impacts. For example, for separation assurance, a resolution for a potential conflict is computed based on parameters such as a time horizon, which vehicle to maneuver, along with any objectives to optimize and constraints to observe.
4. **Action implementation (A):** Implementing the solutions by taking the appropriate actions. For example, for separation assurance, a resolution maneuver is communicated to the vehicle(s) which performs them to resolve the conflict.

B. Agents

Agents are entities which exist within an architecture and execute functions therein. Agents can be both human and non-human/automation. It is common, however, that the automation agent will team with a human agent. For example, an air traffic controller (ATCo) nominally performs the action implementation step of maintaining separation in their sector by verbally communicating with pilots. The ATCo may be assisted in the process by air traffic control (ATC) automation, such as the En Route Automation Modernization (ERAM) tool, which can perform much of the IISA portion of separation assurance.

Several agents are involved in UAS operations in addition to the traditional agents involved in manned operations. For this paper, we will group agents into the following five categories for simplicity:

1. **Airspace service provider (ASP):** Refers to human providers of airspace services, which includes here flow management and separation services. For simplicity, no distinction is made in this paper between public and private service providers. Also known at ATC.
2. **ASP automation (AUT):** Automation providing support to ASP.

3. **Remote pilot (RP):** A remote operator of the unmanned aircraft, which includes potentially a flight crew and dispatchers.
4. **Ground station (GS):** Refers to the automation that provides support to the RP, with the generic interpretation of the term "remote pilot".
5. **Unmanned aircraft (UA):** The vehicle, including any automation onboard to assist the vehicle.

C. Levels of autonomy

The levels of autonomy, or how independent an agent can act with respect to another agent, available within an architecture are another aspect which will impact the final allocation of a function. In Fig. 1, there are three axes. Along the vertical axis are functional groups (e.g., air traffic management services such as safety). Each of these functional groups can be decomposed using the IISA cognitive model. These functional groups are listed on the vertical axis to show their relationship to the other two axes. That is, the axis displays a list of possible functional groups and is not all-inclusive, nor does it necessarily show a relationship between the various functional groups (i.e., from least important to most important). Using the framework in Idris *et al.*, there are two horizontal axes along which autonomy can be increased: the automation level and the control locus, see Fig. 1. The automation level dictates the level of human-machine teaming that occurs, from fully human controlled to fully machine controlled (i.e., fully automated). The control locus describes the relationship between a central agent and edge agent(s). For example, the central agents could be the service provider and the edge agents could be the vehicle/operator. However, within each grouping, there could again be a central and edge agent. For example, the central agent could be the service provider (e.g., ASP) and the edge agent could be the RP/UA. However, within the RP/UA grouping, there could again be a central agent (the RP) and an edge agent (the UA). While numerous examples of levels of autonomy exist in literature [12, 13], we have chosen five for the current work. The five automation levels are defined as:

1. **Human Control**: The function is performed entirely by the human with no assistance from machine/automation.
2. **Shared Control**: The human and the machine/automation perform the function in a cooperative manner (i.e., with decision support from automation). The machine/automation can perform the function with human approval.
3. **Supervisory Control**: The function is performed by the machine/automation with monitoring, teaching, and/or intervention from the human as needed. The machine/automation can perform the function without human approval and will inform the human. The human may intervene when the human decides.
4. **Automated Control**: The machine/automation performs the function independently without any involvement from the human, except when the machine decides (e.g., the machine's self-monitored performance degrades below a set level).
5. **Fully Automated Control**: The machine/automation performs the function independently without any involvement from the human. The machine/automation decides when and how to perform the function. The human is never needed to control the system.

The five control locus levels are defined as:

1. **Centralized Control**: The central agent performs the function in its entirety.
2. **Collaborative Control**: The central agent collaborates with other agents to perform the function.
3. **Delegated Control**: The central agent delegates control to another agent or agents and can intervene when needed.
4. **Distributed Control with Oversight:** Edge agents (i.e., non-central agents) maintain full authority and perform the function in its entirety, while the centralized agent can only intervene and take over if invited by the edge agent(s).
5. **Fully Distributed Control:** Edge agents (i.e., non-central agents) maintain full authority and perform the function in its entirety.

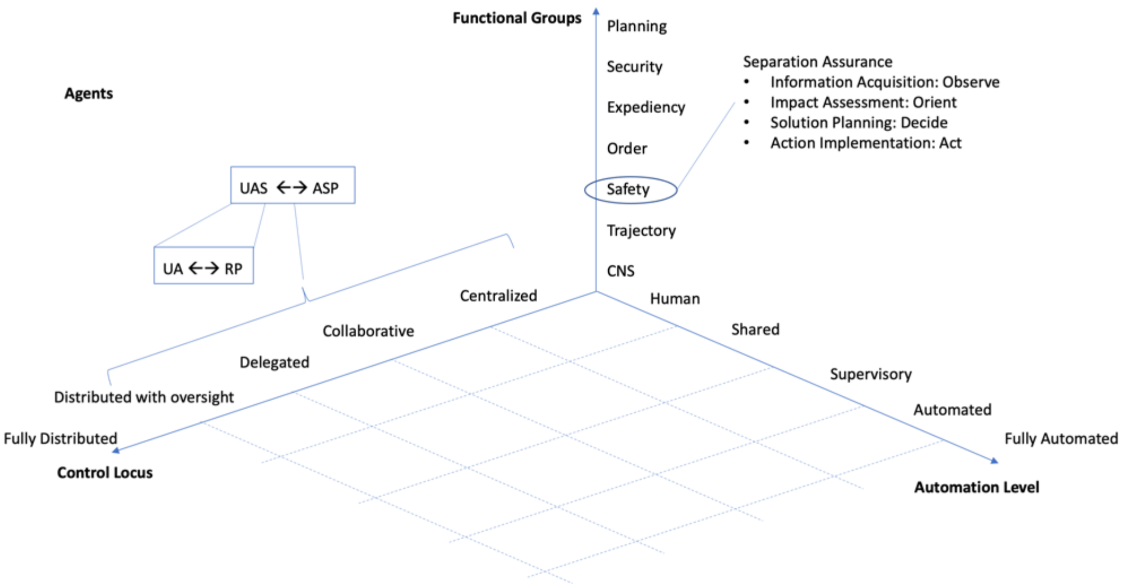

Fig. 1 Levels of Autonomy.

D. Operational context

To properly allocate functions to agents, the uncertainty and complexity of the function must be considered. While several methods of determining the uncertainty and complexity of a function have been proposed [4,8], these considerations can be generically classified as endogenous or exogenous.

1. *Endogenous context*

Endogenous considerations refer to the perception of complexity of a task by the agent performing the task. This subjective complexity is affected by the level of skill, knowledge, and expertise of the agent in the performance of a task in a particular operational environment, as suggested by Idris *et al*. Hence, it also depends on the ability of the agent to learn and adapt to the dynamic – and potentially uncertain – changes in the environment. A higher level of learning results in the expertise needed for the agent to perform the task autonomously. This learning may apply to a human agent, as well as to a machine, where machine learning helps advance its ability to perform the task autonomously. In some cases, the complexity inherent to the task may be such that the agent (automation or human) is incapable of performing the task.

2. *Exogenous context*

Exogenous considerations, especially those that create the operational context, can have a significant effect on the functional allocation process. For example, the class of airspace, the phase of flight, the level of equipage, and the weather conditions are all considerations which can affect the functional allocation. Fig. 2 compares two examples of complexities in the environment in which the UAS may operate. In Fig. 2a, at San Francisco International (KSFO), the terminal environment is busy with other traffic, there is water nearby, and the airport is often foggy. In Fig. 2b, at Jackson Hole Airport (KJAC) in Jackson, Wyoming, the high-altitude airport is surrounded by mountainous terrain, and frequent cold, wintery weather can lead to a higher risk of runway excursion and aircraft icing.

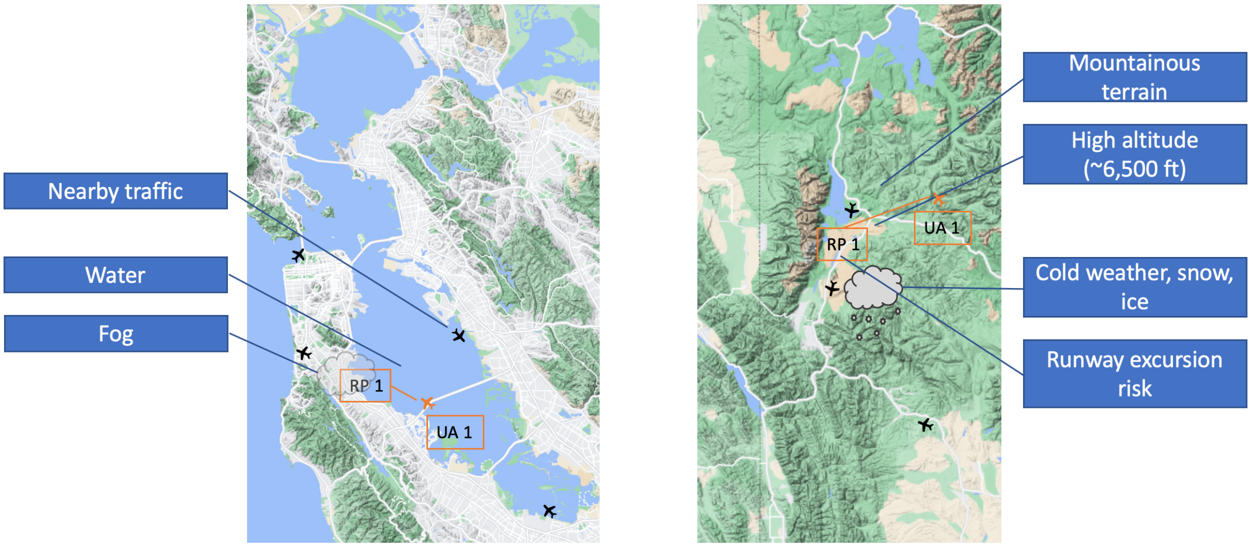

Fig. 2 Example exogenous considerations in the terminal environment at a) KSFO and b) KJAC. Background map data © 2022 Google.

Another operational context of particular importance to UAS operations is when the C2 link is either partially or completely lost. The ability of the RP to command and control the UA is hindered or completely lost in these situations, which may be classified as a contingency in need of management or even rise to the level of emergency situations. Key research questions are: "What is the proper functional allocation in terms of minimum automation required on the UA and what are the clear procedures and responsibilities for all the human agents in the system that, when combined, are needed in order to maintain the required level of safety under lost C2 link (LC2L) conditions?".

IV. Architectures and Agents

An architecture is the foundation upon which a functional allocation takes place. Inherent to an architecture are the physical aspects – the Communications, Navigation, and Surveillance (CNS), the UA's Command and Control (C2) link, and the airspace structure – and the agents. The elements of an architecture consist of the agents and their interactions with each other. The physical aspects and their related constraints and regulations will dictate which agents can execute a function and interact. For example, if UA can only land using a radio line-of-sight (RLOS) signal, then operations will be limited to airports at which RLOS signal is available. The RPs then will have to either be co-located at the airports to utilize the RLOS signal, or a relay system from the RP's location to the airport will need to be in place. This limitation will then impact the functional allocation process, especially in contingency management situations. The airspace structure (e.g., the class of airspace, the presence of corridors, etc.) will have similar impacts on the process. Fig. 3 shows the main architectural aspects described in this section.

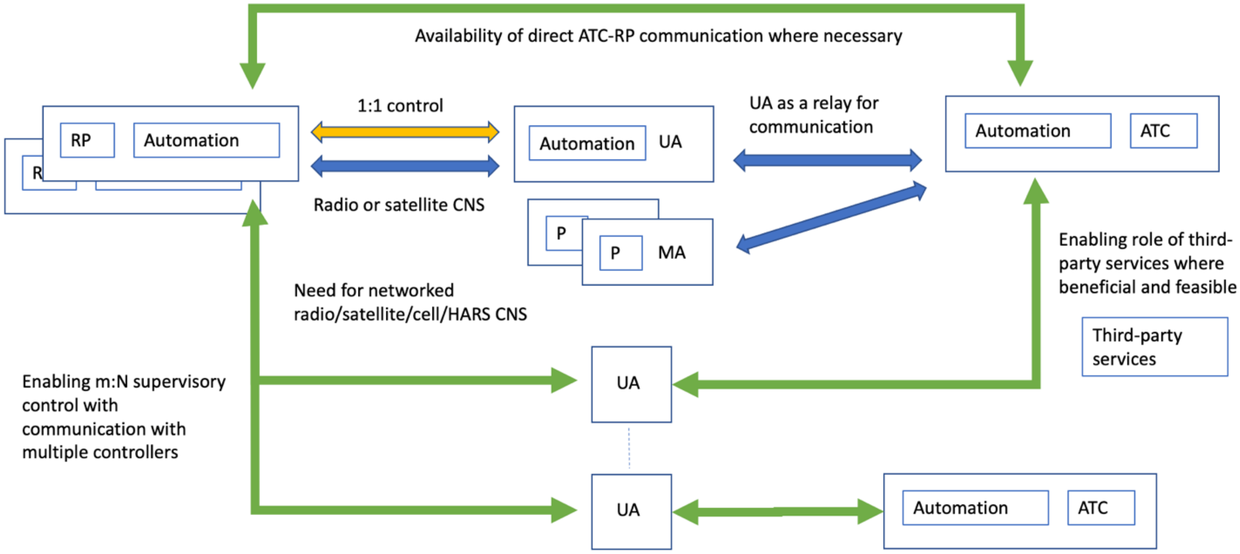

Fig. 3 Architectural elements. Initial architecture assumptions are shown with blue and yellow arrows. Assumptions for future architecture possibilities are shown with green arrows.

E. CNS architecture

In Fig. 3, the initial state architecture assumptions are shown with blue and yellow arrows. These assumptions, such as 1:1 RP to UA control via radio or satellite C2 link (yellow arrow) and CNS (blue arrows), are based off current-day operations of remotely piloted aircraft in the United States Department of Defense and NASA. It is assumed that the UA itself will be used as a relay for communication with ATC. The respective agents are shown in the boxes. Both the RP and ATC agents combine a human element with an automation element. The UA also combines the aircraft and automation.

To enable m:N operations and mitigate the shortfalls such operations present, the assumptions and architectural elements need to be expanded beyond current UAS architecture. The expansions are shown in Fig. 3 with green arrows. A mitigation to using the UA as a relay for ATC-RP communication may be the introduction of direct ATC-RP communication channels where necessary. A potentially significant shortfall to m:N operations is simultaneous voice communication with multiple ATC sectors. Using digital communication may mitigate this shortfall to some extent. The ability and flexibility to introduce and assess novel shortfall mitigations is crucial to maintaining a generally applicable framework.

F. Operator-vehicle architecture

m:N operations present many unique architectural shortfalls. An instantaneous snapshot of the shortfalls is presented in Fig. 4. Fig. 4a illustrates a single RP, RP1, located at or near Fort Worth Alliance Airport (KAFW), a cargo-focused Class D airport underneath the Dallas-Fort Worth Class B airspace. RP1 is simultaneously operating four different UA: UA1-UA4. UA1 has just departed from KAFW. UA2 is en route and approaching the D10 TRACON from the southeast. UA3 is taxiing to depart at Waco Regional Airport (KACT), a towered Class D airport. UA4 is entering into the visual traffic pattern at Hearne Municipal Airport (KLHB), a small, non-towered airport. With these four different UA, there may be four or more different C2 link systems which will need to be monitored. Further, the C2 link systems may be of different types (e.g., cellular for UA1, terrestrial for UA2, High Altitude Relay System (HARS) for UA3, and satellite for UA4). Three of the UA are operating in ATC sectors, with UA4 operating in Class E airspace with visual flight rule (VFR) traffic nearby. RP1 would be responsible for communicating with the ATCo for each sector, as well as monitor the common frequency for UA4. Another consideration which will affect the RP's workload and situation awareness is the level of traffic cooperation. Within ATC sectors, the level of traffic cooperation should be high, thus the RP workload should be lessened. However, the traffic near UA4 may be less cooperative, which may increase the RP workload for that UA. The occurrence of any local or systems-level failures (e.g., LC2L, failed sensors) could also introduce significant challenges and increase RP workload.

Fig. 4b illustrates a m:N architecture whereby four pilots are available to operate the same four UAs. There are many schemes that can be envisioned. For example, Fig. 4b shows RP1 operating UA1 in a 1:1 manner, which may be necessary given that UA1 is in a complex terminal area and phase of flight, requiring fast response time from the remote pilot. RPs 2, 3, and 4 are located at a hypothetical airline operations center. RP2 and RP4 are teamed together operating two UAs (UA2 and UA3), both en route but in different ATC sectors. In the figure, it is suggested that RP2 is the one in command while RP4 is in a supporting role, such as monitoring. RP3 is operating UA4 which again may be needed due to the challenging lack of structure and cooperation from traffic that is predominantly VFR. Such architectural choices impact the functional allocation and necessitate that it be dynamic depending on many of the aforementioned factors. The impact of these architectural choices on the functional allocation and its role in enabling lower m:N ratios are discussed in the application example in Section V.

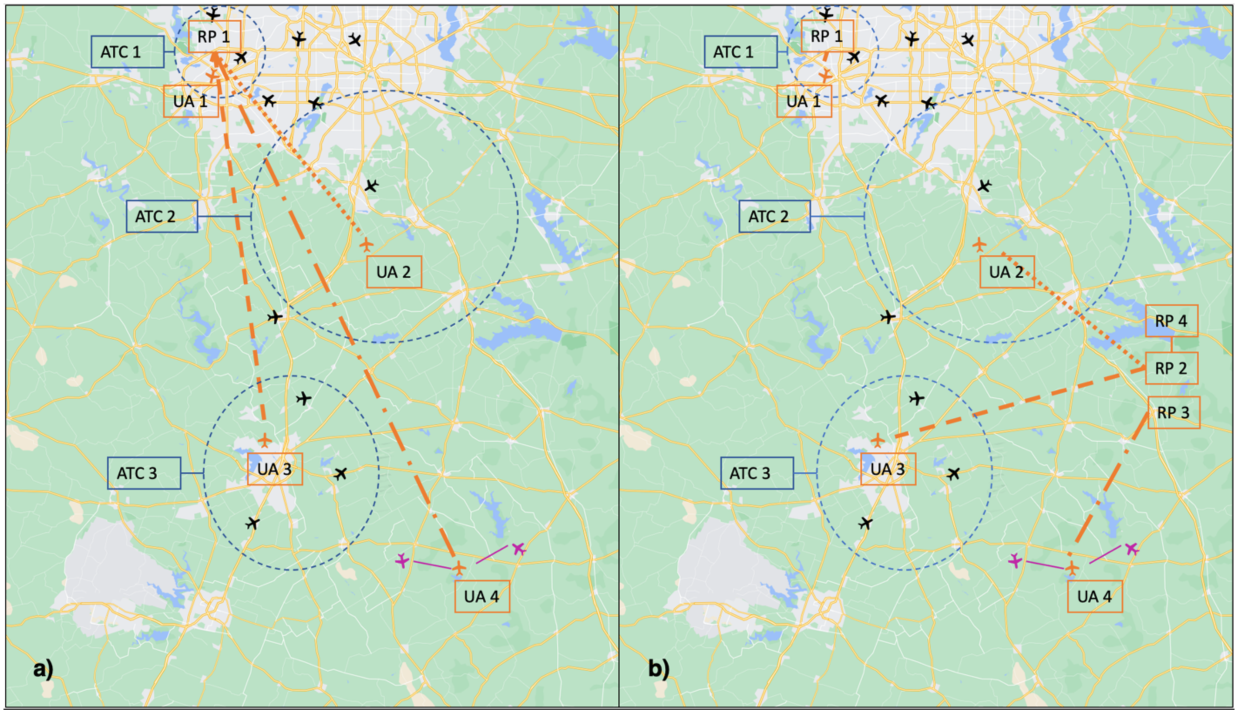

Fig. 4 Instantaneous architectural elements for a) one RP and four UA in a 1:4 configuration and b) four RP and four UA in a 1:1, 2:2, and 1:1 configuration. Background map data © 2022 Google.

G. Airspace structure and airspace service architecture

The physical airspace structure (e.g., classes of airspace, airspace sectors, standard arrival and departure routes) is an important exogenous architectural element. For example, classes of airspace that are positively controlled inherently have agents present, such as ASP, that are able to execute certain functions. In uncontrolled airspace, the ASP agents, like the ATCo, will be unable to be allocated functions they might execute within controlled airspace. Another important airspace-structure element is segregated volumes of airspace which are statically (e.g., military operational areas) or dynamically (e.g., space launch corridors) designed to facilitate special operations.

Volumes of airspace have been suggested recently to accommodate new entrants into the national airspace such as small UAS traffic management (UTM) and urban air mobility (UAM) [9-12]. These volumes of airspace can support novel air traffic management schemes within them and hence offer different opportunities for agent architectures and functional allocations. For example, futuristic concepts envision corridors in the airspace dynamically designed to enable cooperative separation schemes, such as vehicle-to-vehicle coordination, inside them. Third-party agents (other than government and operators) may also be available to provide critical or supplementary airspace services. The nature of such services may be different if provided inside these segregated volumes versus outside. Whether corridors will be a suitable construct for remotely piloted cargo UAS is a subject of ongoing research, yet these segregated sections of airspace will place certain constraints on the functional allocation problem, should they be used. Note that the airspace structure and airspace service architectures, while important factors for functional allocation, are not considered in the application in this paper. While the framework enables the distinction between different airspace service providers, ASP is used as a generic airspace service provider encompassing any third-party agents and the distinction between them is a subject of future research.

V. Application Using Separation Assurance

In this section, we demonstrate the use of the framework by applying it to a high-level functional allocation of the separation assurance function. For this application, we lump the service provider agents into one agent we call the ASP without making a distinction, for example, between public and private providers. It should be noted however, that for the separation assurance function the ATCo is the most relevant airspace provider. Similarly, we lump the operator agents such as pilots and dispatchers into one agent we call the RP, noting that the remote pilot is the most relevant operator agent. Both the ASP and RP are supported by automation which are denoted by AUT and GS, respectively. The UA does not have human agents and consists of only automation.

The framework allows us to organize the function in such a way as to define the solution space. The solution space for this functional allocation exercise is depicted in Fig. 5. Fig. 5a shows (as a green region) the allocation space between the ASP as the central agent and the UAS (including both the RP and GS) as the edge agent. The allocation space limits the automation support for the ASP to be of the form of shared control, implying that we do not consider the ASP automation being able to assume separation authority without the human being in the loop. The motivation for this limitation is based on a preliminary assumption that higher levels of automation for the ASP may not be needed to enable UAS operations in the NAS. Future research will be needed to confirm this assumption, which is made here for the purpose of the example application. The green region in Fig. 5(a) shows that the UAS may need to assume additional authority for separation assurance to enable UAS operations, particularly under m:N architectures. The motivation for this is that the RP may find it difficult to respond to ASP separation instructions while operating many UAs simultaneously, and, as a mitigation, may need to assume a larger role and self-separate from other traffic.

Fig. 5b depicts (as a green region) the allocation space considered for the UAS, between the RP as the central agent and the UA as the edge agent. This allocation space includes high levels of authority for the GS as well as the UA, ranging from shared, to supervisory, to oversight, to out of the loop. The motivation for the expanded allocation space for the UAS (relative to the ASP) is that higher levels of automation are needed in order to enable m:N architectures and safe operation under loss of C2 link. The human RP is assumed to be unable to handle separation instructions from ASP or to self-separate from other vehicles without ASP service, without receiving significant assistance from automation. The GS automation is also insufficient to enable operation under loss of C2 link and hence the solution space must include UA autonomy where the UA is able to perform self-separation when unable to be commanded by the RP. Note that in both a and b of Fig. 5 the allocation space excludes both completely human and completely centralized allocations, as even current-day operations include some level of automation and some level of collaboration.

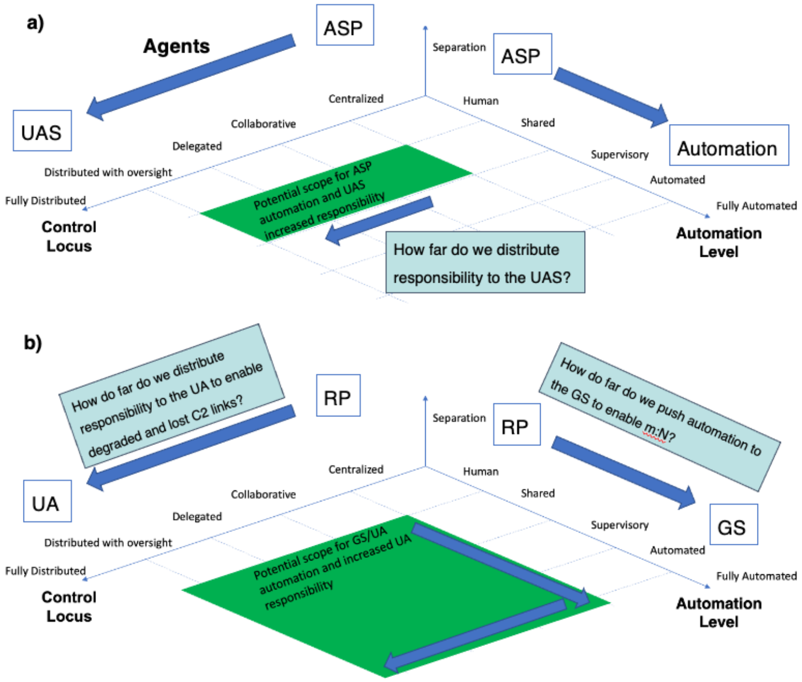

Fig. 5 Functional allocation space for separation assurance application between a) the ASP and UAS and their respective automations and b) between the RP and UA and their respective automations.

Next, we describe a few criteria which can be used for functional allocation decisions. Then we use one of these criteria, namely time criticality, and show how the functional allocation needs to be dynamic based on time criticality. This is done first under a 1:1 nominal architecture and then the dependency on the m:N architecture and on the LC2L conditions are described. In all these cases, some key challenges and research questions are raised regarding the possible functional allocations.

A. Allocation criteria

Several criteria were identified and listed as potential utilities to use in deciding on a possible functional allocation. These criteria include:

1. **Time Criticality:** the time to the potential loss of separation requirements.
2. **Uncertainty Level:** the uncertainty associated with the predicted conflict depends on several factors including how cooperative the traffic is (in terms of sharing its intent), the reliability of the C2 and communications links, among others.
3. **Expertise Level:** refers to the perceived complexity of the task based on the learning level of the agent (skill, rule, knowledge, expertise [8]).
4. **Complexity Level:** refers to task complexity factors such as information processing complexity, problem space complexity, and lack of structure complexity [4].
5. Other factors such as reliability, availability of functionality, security, safety, affordability, among others, see [15, 16].

In the remainder of the section, we use time criticality as a criterion for the allocation.

B. Allocation dependency on time criticality

Fig. 6 shows a series of possible functional allocations along a timeline towards a potential conflict between two UAs that are remotely piloted. Three allocations are shown at three time horizons from the conflict (note that this time discretization is an example and more allocations along the time are possible). The first row of allocations applies to a 1:1 pilot to vehicle ratio in a nominal context. The second and third rows show adjustments to the allocations under m:N nominal operations and under LC2L, respectively. Each allocation is shown in a tableau with the agents as columns and the IISA tasks as rows. The agents include ATC (representing the ASP for separation), automation of ATC (AUT), RP, automation of the RP (GS), and UA. The role of each agent in each task is shown as one of three levels: primary, secondary and none. The primary role, shown as black color, refers to having authority to perform the task. The secondary role, shown as grey color, refers to assisting in the task, either as in a shared/cooperative capacity, in a supervisory/delegated capacity, or in an oversight capacity. A deeper analysis into the level of secondary role is a future research extension. No role at all is shown as white color.

Under a 1:1 architecture with nominal conditions, ATC can assume the primary role when the conflict is far enough in the future that sufficient time is available to acquire the information, assess and resolve the conflict. Automation may be needed to assist ATC especially in the case of a separation involving an UAS. For example, automation may be needed to alert ATC that one or both of the vehicles is an UAS, which implies potentially more latency in its response to ATC instructions, especially if the UA is using satellite for C2 and communication. Automation may also assist ATC in predicting the future conflict and in resolving the conflict using closed trajectories and priorities that are tailored for the UAS behavior. The primary role in implementing the resolution is given to the UA (by necessity since the conflict cannot be resolved unless the UA maneuvers). ATC, RP, and their associated automation have a necessary secondary role to communicate and command the resolution maneuvers. Some additional research questions revolve around: Is there a need for an assistive role by the RP and GS, in providing information, assessments, suggested solutions to ATC? For example, the RP can supply ATC with additional information about the UA maneuvering limitations, risks due to any observed C2 link degradation, or particular trajectory solutions that are preferred for the UA.

As time to the conflict decreases, the primary separation assurance role moves to the RP who performs self-separation with assistance from the GS. The motivation for this is that time is more critical such that there is not sufficient time for ATC to assess a conflict and communicate a resolution. In this phase, airborne or ground-based detect and avoid (DAA) technology is needed to assist the RP. The implementation of the resolutions remains the primary role of the UA with the RP assisting by delivering the commands through the GS. ATC continues to play an assistive secondary role, such as providing situation awareness about surrounding traffic to the RP's who maintain the responsibility to separate. Some research questions in this phase revolve around: Is it necessary to have an assistive role by the UA automation to supplement ground-based automation, in providing information, assessments, and/or suggested solutions? For example, an airborne DAA system may provide alerts over a sufficiently large range supportive of self-separation in this time horizon. Another important challenge is the need for any regulations that are tailored to the UAS self-separation authority and responsibility.

Finally, as the vehicles get even closer to the conflict, the primary separation assurance role moves to the UA because there is no time for the RP to react. Reliance shifts to be on the UA automation (such as airborne DAA or collision avoidance technologies) with possible assistance from the ground-based automation (such as a ground-based DAA system), which may be needed to supplement the accuracy and reliability of the airborne system. Some questions here revolve around the following questions: At what point in time does reliance on the RP in a primary role stop being safe, meaning the UA must avoid collision autonomously with only optional assistance from the RP? Does the RP maintain the ability to monitor and intervene in a supervisory role and for how long can the RP maintain this ability before it becomes prohibitive to do so and they must trust that the UA is acting appropriately? If the UA has the authority, should the RP remain responsible for the actions of the UA?

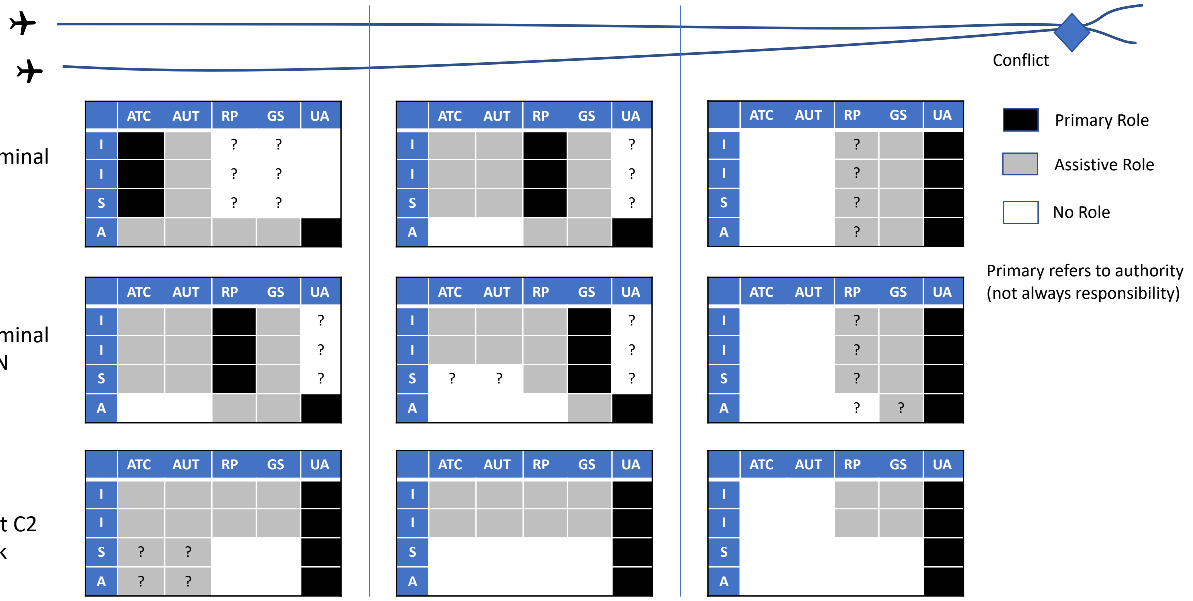

Fig. 6 Dependency of separation functional allocations on time criticality, m:N ratio and loss of C2 link.

C. Allocation dependency on m:N

With an m:N architecture where the RP is operating multiple UAs simultaneously under nominal conditions, ATC may not be able to assume the primary role even when the conflict is far in the future because the delay in the RP response (while handling multiple UAs) precludes the ability of ATC to acquire the information and assess and resolve the conflict in a timely manner. Moving the primary separation assurance role to the RP is one mechanism to enable m:N operations by performing self-separation rather than depending on ATC. However, automation is needed to assist the RP who is handling many UAs and is already busy with supervising their aviate and navigate functions. Automation assists the RP in predicting and resolving the conflict. The primary role in implementing the resolution is given to the UA by necessity, with assistance from the RP and GS automation to communicate and command the resolution maneuvers. Some additional research questions revolve around: Moving the primary role to RP may need regulatory support. What role does ATC maintain, such as assisting in situation awareness about surrounding traffic and sharing conflict assessments, potentially even suggesting resolutions? What is the role of GS and UA and what are the minimum levels of automation needed in the GS and the UA to enable RP self-separation while operating many UAs? Is there a need to expand on the detect and avoid technology to support the RP in self-separation over a long time horizon?

As time to the conflict decreases, the primary separation assurance role moves from the RP to the GS with assistance from the RP. The motivation is that time is more critical such that there is not sufficient time for the RP, who is handling many UAs, to predict, assess and resolve conflicts. In this architecture, automation is needed for information acquisition, impact assessment, and solution planning to enable m:N operations. The automation can be in the GS rather than on the UA because the C2 link is assumed to be working and reliable. In this phase, detect and avoid technology – airborne and/or ground-based – may be used not only to advise the RP, but also to plan and execute resolutions in which the RP may play a supervisory or simply an oversight role. The implementation of the resolutions remains the primary role of the UA with the GS assisting by delivering the commands. There are some additional research questions in the phase: How is trust in the GS and UA automation achieved and what is the required role of the RP in terms of providing supervision and oversight of the automation depending on the trust in the automation? When moving the primary role to GS automation, does the RP stay responsible for the GS actions? What role does ATC maintain and can ATC automation directly support the GS and UA automation without human involvement?

Finally, as the vehicles get even closer to the conflict, the primary separation assurance role moves to the UA because there is no time for the GS to react and send the information or resolution to the UA. This involves still more research questions: When moving the primary role to the UA automation, does the GS automation still assist and how (e.g., by providing ground-based situation awareness to the UA)? Can RP still assist, or must they trust that the UA is acting appropriately

D. Allocation dependency on LC2L context

Under LC2L conditions, neither ATC nor the RP can command the UA and resolve a conflict, at any time horizon. Ensuring safe operations under LC2L necessitates that the UA automation maintains the primary role and authority for separation assurance. While there are assistive roles ATC and the RP can play (e.g., alerting other traffic to the presence of an UA in a LC2L state and its probable course), there are limitations to these roles. Even if ATC assisted by separating the other traffic under their control from the UA, there still exists a need for the UA to self-separate, especially from non-cooperative VFR traffic and from other UA's simultaneously under LC2L. As time to the conflict decreases the ability of ATC to assist in this situation, the ATC function diminishes to only raising situation awareness and eventually may disappear as shown in Fig. 6. The RP (and GS), on the other hand, cannot have a role in the solution planning and action implementation steps, given the lack of link to the UA. They can assist in raising situation awareness of ATC and of other pilots and RPs through sharing relevant information and impact assessments through alternate communication links. Some research questions here are the following: How can predictable LC2L behavior be ensured? What assistance can ATC and RP provide to UA in LC2L conditions? For example, can they share situation awareness with other traffic and move other aircraft away from the UA's anticipated flight path? As depicted in the tableaus in the figure, their ability to assist diminishes as time to the conflict decreases, and hence complete reliance on the UA's self-separation capabilities becomes more critical.

VI. Concluding Remarks

An autonomy framework has been developed for decomposing and allocating the functions necessary for safe, orderly, and efficient flight among the human and automation agents of a remotely piloted aircraft system. The framework was extended to capture the dependence of the functional allocation on the system architecture (particularly the RP to UA ratio m:N) and on the operational context such as LC2L conditions. The framework is intended to help determine what functions should be allocated to automation and to edge agents (such as the remote pilot and the vehicle) to enable scalable m:N operations under nominal conditions and safe operation under LC2L conditions. Finally, the framework was applied to an example functional allocation of separation assurance which highlighted the dependence on three criteria: time criticality, m:N, and LC2L. A number of challenges and research questions were identified. The work will be extended to: (1) additional functions such as integration of the UA into traffic patterns and following other traffic in the pattern; (2) dependency on other criteria such as the complexity of the function or the operations context; and (3) refinement of the definitions of the primary versus secondary assistive roles of the different agents along the autonomy scales.

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