2013 Aviation Technology, Integration, and Operations Conference
August 12-14, 2013, Los Angeles, CA

AIAA 2013-4241

A Systems-Based Approach to Functional Decomposition and Allocation for Developing UAS Separation Assurance Concepts

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In integrating Unmanned Aircraft Systems (UAS) into the National Airspace System, separation assurance is one of the important air traffic services for ensuring safe operations of air traffic. This paper describes an approach to develop a range of operational concepts by describing what functions and technologies are required to maintain safe separation of unmanned aircraft and how those functions are allocated and distributed across primary system elements, such as air traffic controllers, automation systems, aircraft onboard systems, and UAS ground control stations including UAS pilots. A framework proposed in this study identifies key functions and capabilities by decomposing high-level system goals into smaller functions to achieve them hierarchically and also identifies primary system elements to perform the identified functions by decomposing the whole system into smaller systems hierarchically. The framework represents hierarchical functional/physical structure and allocation of functions across system elements at different levels to generate a range of potential separation assurance concepts systematically. The detailed representation of functional decomposition and allocation enables an application of the framework for recommending levels of automation (LOA) developed based on human factors engineering principles. The detailed functional decomposition and allocation framework to develop a concept of operations provides additional analysis capabilities: stability, workflow, and task-load analysis to examine the completeness, correctness, and balance of functional decomposition and allocation schemes for concept development without requiring complex simulations. This paper demonstrates the framework through a case study of providing separation assurance functions for UAS operating in en-route and transition airspace in the Next Generation Air Transportation System (NextGen) timeframe.

I. Introduction

Integrating Unmanned Aircraft Systems (UAS) operations into the National Airspace System (NAS) in a safe and effective way is a high-priority capability for the Next Generation Air Transportation System (NextGen) because many potential government and civil users of UAS are severely restricted or prohibited from operating in the same airspace as crewed aircraft.[1] Separation assurance (SA) is one of the important Air Traffic Management (ATM) functions that ensure safe separation of unmanned aircraft with other traffic and enable UAS to avoid other hazards, such as severe weather, restricted airspace, or terrain. Separation assurance of UAS with significantly different performance characteristics and unique flight profiles from existing crewed aircraft may require significant changes in the roles and responsibilities of air traffic service providers interacting with each other in complex ways to ensure safe, efficient, and consistent UAS operations throughout the NAS.[2,3] Current ATM systems for flight planning, traffic flow management, and separation management may not be able to account for the unique profiles, flight dynamics and distributed architectures of UAS.[1]

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An operational concept for separation assurance of UAS can be defined by describing what functions and technologies are required to maintain safe separation of unmanned aircraft in civil airspace and how those functions are allocated and distributed across primary system elements, such as air traffic controllers, automated ATC systems, aircraft onboard systems, and UAS ground control stations including UAS pilots/operators. Typically, the overall system performance derives from the collective contributions of all entities (system elements) within the system, ranging from automated systems to the dynamics of new types of aircraft (like different types of unmanned aircraft) to the human pilots and controllers. The introduction of UAS may induce more complex interactions and additional coordination among primary system elements in the NAS to accomplish their goals and missions. Therefore, developing separation assurance concepts for safely operating UAS in non-segregated civil airspace requires a systematic approach for identifying and analyzing complex interactions among system elements as well as functions of individual system elements to separate unmanned aircraft from other aircraft and hazards. However, previous research on UAS integration has focused on providing to UAS an onboard "sense and avoid (SAA)" capability rather than an operational concept for how such a capability will interact with existing separation assurance operations of manned aircraft.[4,5,6]

The purpose of this paper is to describe a systems-based approach employed to develop a range of concepts intended to explore a range of allocations of UAS separation assurance functions. In this study, a functional decomposition and allocation framework was developed based upon systems engineering principles in order to bring concept development together with functional analysis methodologies to create separation assurance concepts for UAS. The framework introduces a multi-dimensional concept map to represent several independent factors that affect the separation assurance operations of UAS. As a core component of the framework, a two-dimensional functional decomposition and allocation matrix (FDAM) was also developed and constructed using hierarchical task analysis and function allocation methods to create a variety of potential separation assurance concepts systematically for UAS integration into the NAS. The framework identifies key functions and capabilities by decomposing top-level system goals into smaller functions to achieve them hierarchically and also identifies primary system elements to perform the identified functions by decomposing the whole system into smaller systems hierarchically. The resulting FDAM represents hierarchical functional/physical structure and allocation of functions across system elements at different levels to generate a range of potential separation assurance concepts systematically. The detailed functional decomposition and allocation framework enables applying methods for recommending appropriate levels of automation (LOA) and provides additional analysis capabilities: stability, workflow, and taskload analysis to examine the completeness, correctness, and balance of functional decomposition and allocation schemes for concept development without requiring complex simulations. It should be noted that the purpose of this paper is not to develop a complete set of operational concepts for all air traffic services in the various phases of UAS operations in the NAS. Therefore, our approach does not prescribe which concepts of operations should or should not be developed in a particular system. This paper demonstrates the systems-based method through a case study of providing separation assurance concepts for UAS operating in en-route and transition airspace in the NextGen timeframe.

II. Background

Separation assurance of all aircraft requires controllers for safely maintaining a legally specified separation minima between aircraft; for example, typically 5 nautical miles horizontally and 1000 feet vertically in en-route and transition airspace. Various automation systems and operational concepts for separation assurance of crewed aircraft have been proposed and studied to increase capacity, safety, and efficiency of the NAS.[7,8,9,10] A brief review of separation assurance operational concepts for the NextGen and an analysis of options for separation assurance roles and responsibilities among different concepts have been conducted.[11] Recently, Bilimoria (2011) also provided a comprehensive literature survey of separation assurance in ATM and categorized by allocating functions along the air/ground and human/automation axes with an emphasis on the importance of function allocation in developing a range of future ATM concepts.[12] Several operational concepts and physical architectures for UAS operations in the NAS have also been proposed based on the type of Unmanned Aerial Vehicle (UAV), the path of surveillance information, and the control capability of the UAV onboard systems (or level of UAV autonomy).[13] However, no clear methodology based on systems engineering and human factors engineering principles has been applied to try to define the roles and responsibilities of various system elements including human operators and automation (or decision support) systems in the development of such operational concepts.

A Concept of Operations (ConOps) development begins with a clear understanding of the goals of the proposed concepts as well as its integration into the operational environment or domain (e.g., terminal, tower, en route). As shown in Fig. 1, there are five levels of ConOps within the concept hierarchy developed for the FAA Air Traffic Organization (ATO).[14] A concept of integrating UAS into the NAS is a Level 2 (or service-level) concept in the concept development hierarchy, which provides a high-level technologically neutral description of a strategic set of concepts and/or capabilities for delivering improvements to the NAS. Level 3 concepts can be developed and refined from a functional decomposition of one or more of the services described in level 2 that support level 1 concepts. Level 3 concepts describes how the new function or capability will be used in nominal and/or off-nominal operations and should be in sufficient detail to be used in concept evaluations/validation activities (either fast-time or human-in-the-loop simulations). This study focuses on the development of level 3 operational concepts.

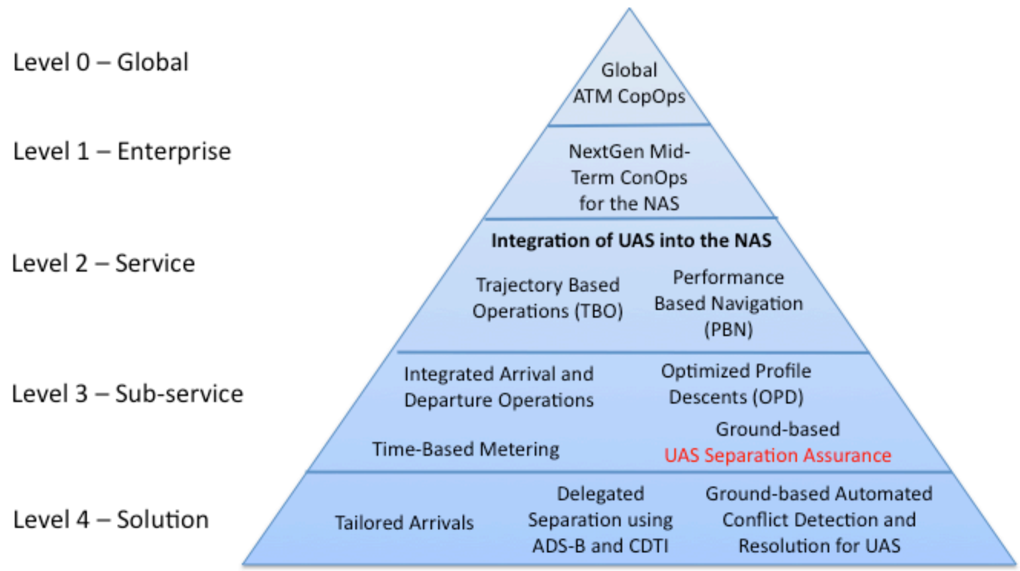

Figure 1. Concept Development Hierarchy.

The purpose of a ConOps is to describe how the various system elements could be operated as a whole system to successfully achieve desired objectives for a proposed concept/system.[15] Therefore, one fundamental premise of this paper is that "a range of separation assurance concepts are formulated by identifying and allocating separation roles and responsibilities among primary system elements within the NAS, such as pilots, controllers, automation systems, and air navigation service providers in the various phases of flight".[12] Another fundamental premise is that a concept of operations should be driven by a mission and goal statement to describe system characteristics from an operational and functional perspective and how a set of capabilities will operate to achieve desired objectives for a proposed system from the users' perspective.[16]

Based on the premises, work domain/task analysis and function allocation methods that have been widely used in human factors engineering will play an important role because they determine how certain processes, roles, or responsibilities related to key functions of the system of interest can be distributed among primary system elements to achieve high-level goals and missions of the system. However, those methodologies have not been explicitly used in the development of operational concepts of complex systems, such as the air traffic management system. Instead, the traditional function allocation studies usually have been focused on the design of a specific system or its interface, deciding a best (or optimal) allocation of functions between humans and machines (automation) according to their capabilities and strengths, rather than focusing on the development of operational concepts.[17,18]

In this study, an approach of using a hierarchical decomposition method and a functional allocation method is taken to help identify required separation assurance functions for UAS from the top-level concept goals and allocate the identified functions to system elements within the NAS in order to develop a range of operational concepts in a systematic manner. The idea is that a concept can be described by the functions that are required to be performed to achieve high-level concept/system goals and their associated requirements.[14] It will be essential to better understand complex system behaviors in terms of functions in order to develop an effective operational concept. A formal functional analysis approach, such as a hierarchical task analysis (HTA)[19] or a work domain analysis (WDA),[20] provides a methodology to analyze and represent the functional behavior of a complex system and to convert top-level operational goals of the system to progressively more-detailed task descriptions to detailed functional descriptions in a systematic way.

In this paper, we consider the NAS integrated with UAS as a large-scale complex socio-technical system in which humans and automation systems are interacting with each other in a complex way to achieve the goal of the overall system as well as the one of individual system elements. Therefore, all tasks performed by humans are considered and defined as functions in this study. In the development of separation assurance concepts for UAS, therefore, it is critical to conduct an analysis of the "concept space" using formal functional analysis methods to systematically identify all of the required separation assurance functions from top-level system goals and identify a set of required capabilities to perform the identified functions. However, these functional allocation approaches have not been applied yet to developing a variety of separation assurance concepts for integrating UAS into the NAS. In our approach, all functions/tasks that are performed by any system elements (including humans and machines) will be identified using the well-known HTA technique developed by Shepherd (1989).[19]

The concept development approach can be described at a high level as an iterative refinement of concept classification and function allocation as depicted in Fig. 2. As the concept matures, it becomes more detailed and refined in terms of its operational description and its relationship to higher-level operational concepts. The main objective of this study was to apply a systems engineering approach to identify and represent required separation assurance functions for UAS operations in the NAS and define various separation assurance concepts in a systematic and consistent way. To this end, a high-level framework was developed that shows a sequence of tasks as depicted in Fig. 2.

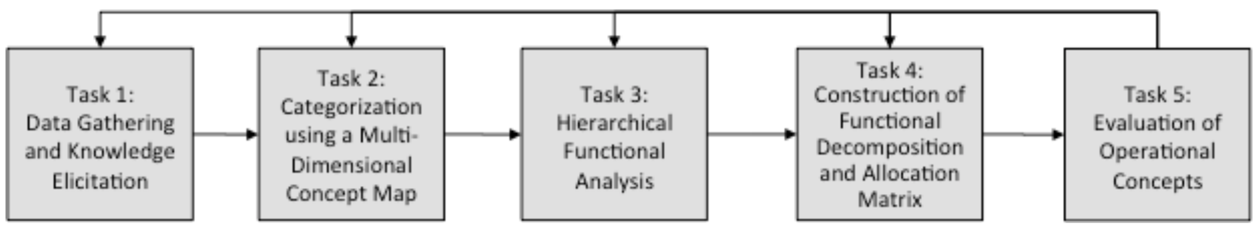

Figure 2. A Framework for Developing Separation Assurance ConOps for UAS.

As the first task of the framework, information about separation assurance functions of UAS in the current ATM system or in the future ATM system should be gathered through rigorous literature surveys and knowledge elicitation from Subject Matter Experts (SME) to understand about the work environments in which separation assurance functions are performed for UAS. The information gathered from this task can be used to categorize separation assurance concepts at a high level based on identified important factors that may significantly impact the development of separation assurance concepts of UAS in the NAS. The constructed high-level concept map in task 2 can be used in defining the operating environments and high-level description of possible separation assurance operations in each category based on available capabilities and technologies in the operating environment. As a next process, an HTA method is used to identify more detailed functions required to perform for separation assurance of UAS and to construct a multi-level functional hierarchy. The resulting hierarchical functional architecture is used to construct Functional Decomposition and Allocation Matrix (FDAM) in the next task. The potential concepts of operations generated from the previous task should be evaluated and/or validated as the last task of the concept development framework.

In this paper, based on the limits and scope of this study, Task 2 to Task 4 in the framework will be highlighted through a case study of providing separation assurance services to UAS operating in en-route and transition airspace. The following sections provide a detailed description of each of the tasks.

III. Multi-Dimensional Concept Map

The main objective of developing a concept map is to describe an overall categorization of separation assurance functions along with multi-dimensional factors that affect the separation assurance operations of the UAS in the NAS. This concept map provides a high-level categorization that guides to generate separation assurance concepts at a high level in the early development phase of concept development.

Separation assurance concepts that have been proposed for manned aircraft are typically categorized into several concepts based on whether separation assurance functions are centralized or distributed among ground-based air traffic controllers and pilots and to what extent those functions are automated.[11,12] As shown in Fig. 3, therefore, separation assurance concepts for UAS operating in the NAS can be categorized similarly by the following factors: (1) who has control authority and is responsible for separation assurance of unmanned aircraft (unmanned aircraft systems vs. air traffic control systems or distributed vs. centralized); and (2) what levels of automation and autonomy of air traffic control systems and unmanned aircraft systems will be available. The concept map was created and categorized based on the function allocation space that was developed and categorized for separation assurance of crewed aircraft.[12]

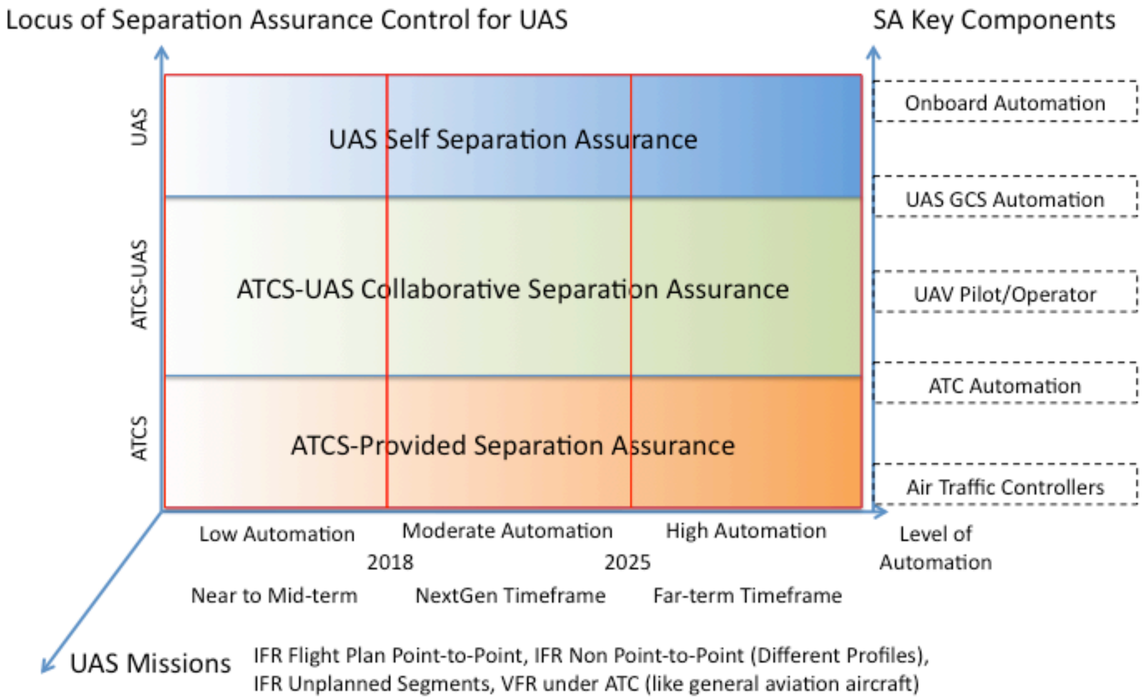

Figure 3. A Concept Map for UAS Separation Assurance.

1. Locus of Separation Assurance Control for UAS

As described, one of the critical factors in developing an operational concept is to determine who's going to perform the part or whole of separation assurance functions (e.g., ground air traffic control system, unmanned aircraft system, or distributed between air traffic control system and unmanned aircraft system). Each category can have various operations along with the level of automation.

- *Air Traffic Control System (ATCS)-provided Separation Assurance:* Ground-based ATCS including air traffic controllers and ATC automation systems (e.g. ERAM) provides separation assurance services to UAS. For example, human controllers interacting with automation systems are responsible for predicting, detecting, and resolving traffic conflicts of unmanned aircraft within controlled airspace. A range of high-level operational concepts can be generated based on the level of automation at each timeframe. This category may require minimal changes to the current ATC infrastructure, operations, and technologies.
- *ATCS-UAS Collaborative Separation Assurance*: In this category, the responsibilities of separation assurance functions can be distributed between unmanned aircraft system and air traffic control system. For example, the controller can delegate responsibility to the UAS operator for resolving a conflict with another designated aircraft while being responsible for conflict detection and resolution of all other aircraft in the same airspace. A range of collaboration schemes can also be developed in this category by shifting some of the separation assurance functions to UAS in predicting and resolving conflicts of unmanned aircraft based on available information and technologies to UAS and communication methods between UAS and ATC facilities.
- *UAS Self Separation Assurance*: In this category, the UAS is responsible for predicting and resolving conflicts without coordinating with air traffic controllers. The air traffic controller does not need to provide any separation assurance services to UAS, but should provide other services such as traffic flow management. This categorization may require additional capabilities or equipage requirement for UAS to maintain safe separation from other aircraft, such as advanced Sense and Avoid (SAA) capability.

2. Level of Automation Capability

Another primary dimension to develop various SA concepts is the level of automation capability. The SA concepts for integrating UAS into the NAS will be dependent upon the capabilities of the NAS, which are envisioned and defined for different timeframes in NextGen ConOps documents.[1] This dimension of categorization provides a description of operating environments in which UAS are operating in terms of enabling communication, navigation, and surveillance (CNS) capabilities and automation technologies.

As described earlier, a separation assurance concept can be created by allocating different roles and responsibilities for separation assurance functions to key concept elements, such as controllers, flight crew, and UAS operators. The realization of a function allocated to an element of the system can be dependent upon the capability of that element or actor to perform that function. For example, while it may be desirable to provide an UAS an ATC clearance via data communications, the realization of such a functional allocation is obviously subject to the availability of data communication capability in the air traffic system. Therefore, in creating the concept map, the available capabilities and limitations should be detailed for each level of automation (defining operating environment at each timeframe) that is used in the development of the concepts. By considering the capabilities and limitations of the domain/environment in which UAS is operating, we can generate various options in each category, such as ATCS-provided SA and UAS self-SA categories as shown in the map.

In this framework, the degree of automation is categorized into the following three levels based on near-term, mid-term, and far-term timeframes as shown in Figure 3. Given the capabilities and technologies in each timeframe, various concepts can be generated along with the locus of SA control functions.

- *Low-Level of Automation Capabilities (Near to Mid-Term Timeframe)*: This category represents near/mid-term air traffic operations in which only a basic set of automation tools will be available for air traffic controllers and UAS. For example, dominant communications between controllers and UAS operators will be voice communications relayed via the unmanned aircraft. The controller will estimate the predicted positions of unmanned aircraft based on flight plan strips or using a vector line and predict potential traffic conflicts with other aircraft just using a distance reference indicator (the HALO or J-ring), which places a 5NM ring around the target aircraft. The controller may also use a basic conflict alert/probe tool. No additional tools for separation assurance of unmanned aircraft will be available at this timeframe. The level of autonomy of unmanned aircraft might be low, requiring mode-control operations similar to Mode Control Panel (MCP)-directed states/modes in a manned aircraft to capture the next control state. The aircraft may be semi-autonomous such that the operator can directly command a vehicle state, but the vehicle will follow a prescribed flight plan autonomously without the operator's intervention. In this category, ground air traffic controllers perform most of separation assurance functions with a basic set of automation tool.
- *Moderate-Level of Automation Capabilities (NextGen Timeframe)*: This category represents NextGen operations in which an advanced set of decision support tools and automation systems will be available for air traffic controllers and UAS operators, though not all the promising technologies and capabilities defined in the NextGen ConOps will be available and mature by this timeframe (2018~2025).[1] It can be reasonably assumed that there will be data link communications between UAS and ATC operational (functional) entities and all aircraft including unmanned aircraft will be equipped with Automatic Dependent Surveillance – Broadcast (ADS-B) capability in Class A airspace. In this timeframe, human controllers might be still responsible for a final decision about separation assurance, but many separation assurance functions can be automated as technologies advance to support the controller for improving overall system performance. For example, ground ATC automation automatically detects long-term and short-term conflicts and suggests a set of conflict-free resolution trajectories that can be modified using a trial planning tool for the controller.
- *High-Level of Automation Capabilities (Far-term Timeframe)*: This category represents far-term operations beyond the NextGen timeframe (2025~). Most of the separation assurance functions can be performed by advanced automation without human intervention if the performance is within the tolerance limits to accommodate significantly increased traffic demand and various types of aircraft.[10] The behavior and performance of the advanced automation is supervised by human controllers and UAS operators for nominal operations, and humans intervene only for off-nominal situations. UAS might be capable of fully autonomous operations under the supervision of the UAS operator. For some separation assurance tasks, the advanced automation might have a responsibility rather than the human in this timeframe.

In addition to level of automation and locus of control, other dimensional factors like UAS types or missions can be considered in developing operational concepts. The types of UAS missions in the future are not just point-to-point flight operations, but typically some form of patterned flight or tracking aerial work activities. Therefore, how the different types of UAS missions and unique UAS performance characteristics potentially affect the separation assurance operations should be investigated from an ATM perspective, although some NextGen capabilities like Trajectory-Based Operations (TBO) may help manage the additional complexity related to the operations of different types of aircraft.[21]

This concept map is constructed at a high level and provides a guideline to categorize concepts based on the locus of separation assurance control and the levels of automation in terms of critical capabilities and limitations of the operating environment. The concept map shows a very high-level categorization and function allocation. Therefore, this map can be used to identify and describe overall operational concepts at a system level, such as UAS and ATCS, along with the available capabilities and limitations. However, this map does not provide more detailed function allocation decisions between key concept elements in each cell of the map without conducting further functional and task analysis. For more detailed function allocation and level of automation (LOA), therefore, it is necessary to decompose separation assurance functions at the system level down into smaller functions at the level of concept elements. The detailed representation of functional decomposition and allocation enables an application of the framework for recommending levels of automation developed based on human factors engineering principles. Recent articles argue that it is desirable to develop more detailed models to identify key sub-functions and capabilities than abstracting functions in allocating functions to improve overall system performance.[22,23,24] Therefore, this study proposes a two-stage process of first classifying potential concepts in terms of their level of automation and their locus of separation assurance control, then performing a functional decomposition leading to allocation of low-level functions to elements of the system.

IV. Functional Decomposition and Allocation Framework

This section describes a structured framework of using functional analysis methodologies to formulate various separation assurance concepts with different function allocation decisions and to support comparisons between potential concepts in a systematic way.

A. Hierarchical Functional Analysis

Once possible UAS operating environments are categorized in the multi-dimensional concept map, the outcome is used to identify required functions in each of the possible operating environments through a hierarchical functional analysis. Hierarchical functional analysis is the systematic process of identifying and describing the functional characteristics a system must perform to accomplish its goals and defining how those functions relate to each other. Various functional analysis methods can be used in system architecture development and functional decomposition to convert goals to progressively more detailed task descriptions to detailed functional descriptions.

For this study, we conducted a hierarchical functional analysis for separation assurance of UAS operating in the en route and transition airspace through a rigorous literature surveys, site visits, and interviews with subject matter experts such as retired en route controllers and UAS pilots to identify separation-related operations and functions in the current ATC operating environment.[25,26,27] This information has been crucial to the functional requirements analysis presented in this document. We used Hierarchical Task Analysis (HTA) to identify required separation assurance functions decomposed from top-level concept goals and a function allocation framework that has been proposed for different types and levels of automation.[24]

HTA method is a systematic process of representing how high-level goals and tasks can be decomposed into lower level functions and defining how those functions relate to each other.[28] Typically, this hierarchical decomposition process continues until a sufficient level of detail is reached based on the purpose of task analysis. The resulting hierarchical functional architecture provides some structure for the description of functions or activities, which then makes it easier to describe how functions fit together and to understand dependency between different functions/activities (performed by either humans or machines).

Understanding and analyzing the required functions of the system is a central tenet of the functional analysis task in order to represent the hierarchical relationship among separation assurance functions of system elements within the NAS, such as air traffic controllers, unmanned aircraft, ground control stations, UAS operators, and Air Traffic Control (ATC) automation systems. A hierarchical functional architecture was constructed through the analysis to represent the functions at all levels of the system hierarchically as shown in Figure 4. This hierarchy is only a portion of the functional architecture, which is not complete until all requirements and other constraints have been appropriately decomposed.

The analysis can begin with a description of the top-level goal of the whole system or a concept of operation. Thereafter, "how" questions direct the analysts or concept developers breaking a particular function. The objective of this step is to develop a hierarchical functional architecture that describes the functions at all levels of the system hierarchically. Separation assurance generates trajectory changes to resolve violations of separation standards or projected conflicts between aircraft or between an aircraft and an aviation hazard, such as obstacles, restricted airspace, or severe weather. Therefore, as shown in Fig. 4, the function F.1, "Manage Separation Assurance of Unmanned Aircraft (UA)", can be decomposed into four first-level subfunctions that are required to accomplish a higher-level function. Next, the functions in the first level are decomposed to the second level. This process continues until all the functions are totally decomposed into primitive functions that can be uniquely allocated to one of the system elements. A portion of hierarchical structure of separation assurance functions for UAS is illustrated in Fig. 4. However, the hierarchical functional architecture doesn't represent who is going to perform which functions, which is critical information in developing operational concepts.

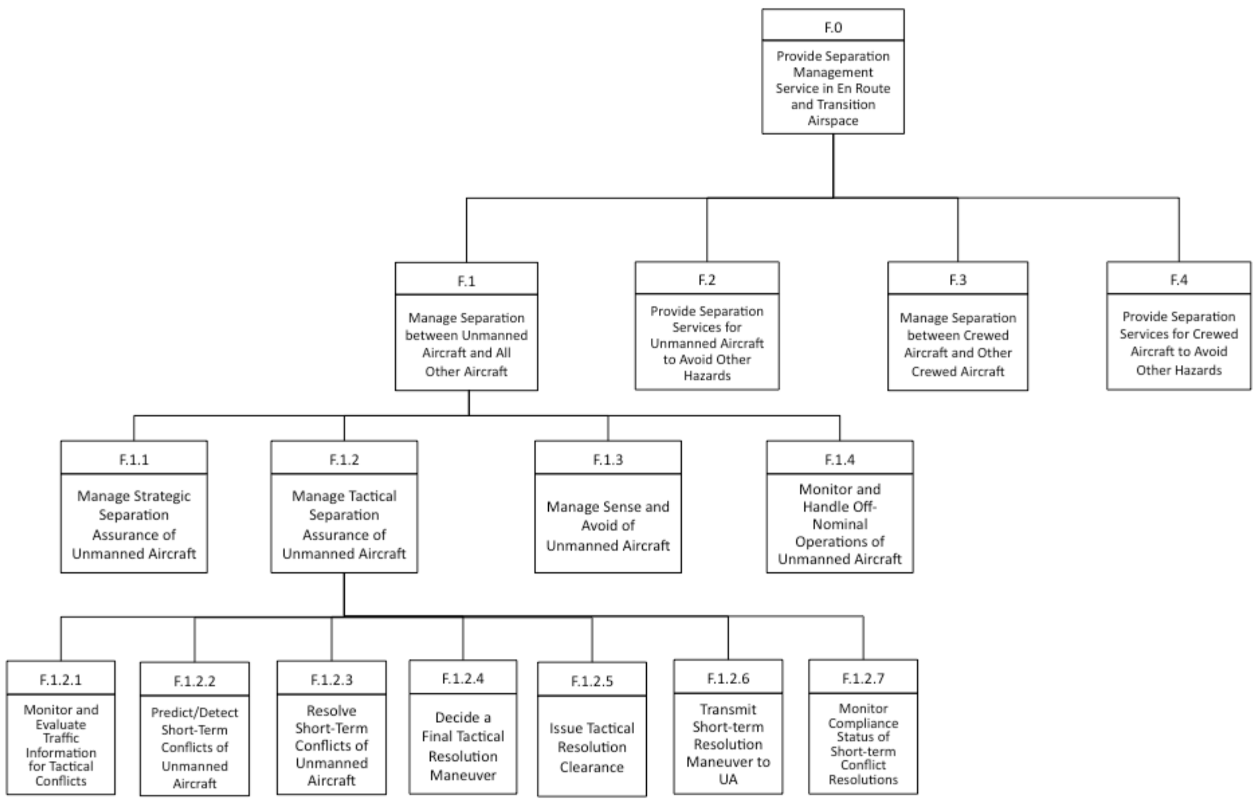

Figure 4. An Example of Hierarchical Functional Architecture for UAS Separation Assurance.

B. Functional Decomposition and Allocation Matrix

The functional architecture constructed through a hierarchical functional decomposition process represents the required functions at the different levels from the top-level concept goals, but it does not show which system elements perform those functions. Therefore, in this study, a two-dimensional functional decomposition and allocation matrix (FDAM) is developed to represent hierarchical functional relationships and function allocations across system elements at the different levels as shown in Fig. 5. The operational concept of separation assurance at this level of fidelity can be described in terms of what functions should be allocated to whom and to what extent to achieve the goal of safe and effective separation of unmanned aircraft.

Basically, the FDAM borrowed the concept of the abstraction-decomposition space (ADS) that has been used in the Work Domain Analysis (WDA) to identify information requirements and constraints of the system's work environment.[20] In the resulting grid of FDAM, like ADS in the WDA, the columns represent the part-whole decomposition. The decomposition dimension represents the different levels of detail required to reason about the work domain. The rows represent the functional decomposition (abstraction) for the different levels of decomposition (system, subsystem, and component).

Function allocation is a traditional human factors method and an essential component of systems engineering for deciding which functions should be carried out by whom (either by humans and by machines) in the early design process of systems.[29] Most approaches to function allocation have been focused on providing a formal and rational method for making best allocation decisions between humans and machines with some ways of comparing trade-offs between possible allocations, such as "Men Are Better At and Machines Are Better At (MABA-MABA)" list.[30,31] The importance of function allocation has been well documented in the literature.[32]

The FDAM provides a methodology for representing required functions to accomplish top-level goals at different hierarchical levels and for representing potential allocation of the required functions to system elements at different system levels in a structured and systematic way. Figure 5 shows the overall schematic of the FDAM to create a set of potential concepts and to provide an overall picture of a proposed concept and its functional decomposition an allocation decisions at the different levels. It will provide researchers, stakeholders, and decision makers a common view of the operational concept that derives the operational changes and requirements. The FDAM needs to be created separately for each of possible UAS separation assurance concepts.

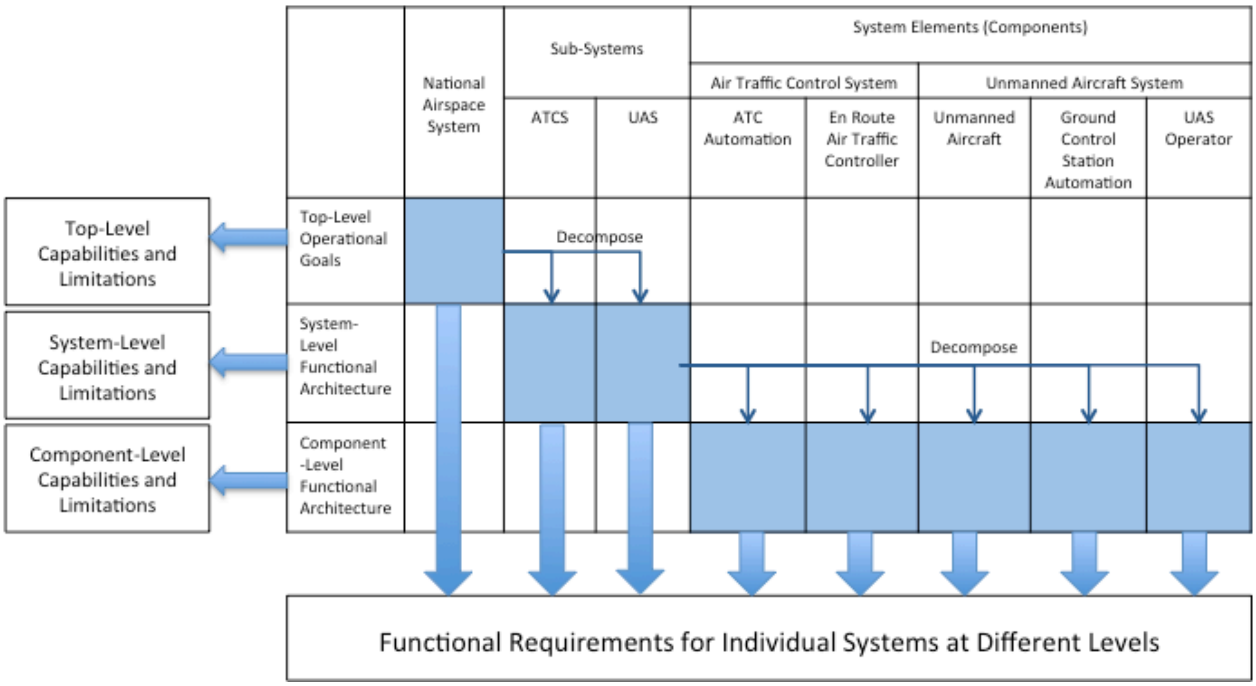

Figure 5. Functional Decomposition and Allocation Matrix (FDAM).

1. Vertical Dimension of FDAM

FDAM is constructed based on the functional hierarchy created in the previous functional analysis process. The vertical dimension of the FDAM represents a hierarchical functional relationship at the different levels of functional hierarchy. Typically, moving down the functional levels answers how particular functions in the system are achieved, whereas moving up reveals why certain functions exist.

The top level of the functional hierarchy (upper-left cell of the matrix) represents top-level operational goals of the whole system (e.g., NAS). This "model" is a very simple statement of the purpose of the system as a whole: Integrate UAS into the NAS in a safe and effective manner. From top to bottom in the vertical dimension of the FDAM, the higher-level goals/functions are decomposed into lower level sub-functions. Functions at the lowest levels of the dimension indicate and describe the primitive functions of the system that can be allocated to be performed by one of the system elements.

2. Horizontal Dimension of FDAM

From the left to the right of the horizontal dimension, a top-level system, such as the NAS, can be decomposed into the subsystems that are physical, functional, or operational entities that operate within an operating environment of the domain and interact with each other in some way to accomplish their goals. Information along the functional decomposition hierarchy results in a different level of functional description of the same task (e.g., issue a clearance vs. press a microphone button). In contrast, information along the physical system decomposition results in a description of a different level of system component (e.g., aircraft vs. navigation display), representing the part-whole relationship of the system.

This physical decomposition of the system continues recursively until the individual system elements/components that are required to perform the primitive actions/functions can be identified or defined. The number of levels for the vertical and horizontal dimensions may vary with the complexity of the system as well as the purposes of the analysis. For example, the NAS can be decomposed into UAS, crewed aircraft, airports, terminal radar approach control (TRACON), air route traffic control center (ARTCC), and air traffic control system command center (ATCSCC). These subsystems can be further decomposed into system elements (or components) as shown in Fig. 5. For example, a UAS is typically composed of six elements: unmanned aircraft element, communications element, ground control element, human element, support element, and payload element.[1] Based on the purpose of the analysis, unmanned aircraft itself can further be decomposed into communication, navigation, surveillance, and flight control systems. Typically, most of complex systems can be represented with three levels of resolution: whole system, subsystems, and system elements.

Human operators, such as air traffic controllers and UAS operators, are critical and integral system elements to accomplish separation assurance goals. Therefore, human operators should be included at the level of system elements in developing candidate concepts to allocate separation assurance functions to them as appropriate to the system architecture, technical capabilities, and operator's capabilities. Operating procedures for human operators can also be derived from the detailed decomposition of functions and its functional workflow including input, output, and triggering conditions.

3. Derived Requirements and Limitations

The requirements for allocating functions to system elements should be derived to ensure the equipment, technologies, and automation capabilities are available to perform their assigned tasks safely and effectively.[14] The assumptions and requirements regarding the future NAS and UAS characteristics should be identified for each level of functional architecture to establish the foundation for developing various operational concepts and to constrain the next-level required functions. As shown in Fig. 5, requirements are identified at each level of a hierarchical structure starting with the top-level requirements imposed by customers and other stakeholders from upper-left cell in FDAM. These high-level requirements are decomposed into functional and performance requirements and allocated across the system. These are then further decomposed and allocated among the elements and subsystems. It is important to note that the functions in the next level of the hierarchy are identified and framed by the requirements and physical architecture defined in a higher level of the hierarchy.[14]

While traditional approach is to what functions should be performed based on available technologies and capabilities as discussed in the concept map, FDAM help identify what technologies or capabilities are required to perform the required functions. From the required functions identified from top-level goals through a hierarchical task analysis, we can derive required technologies and capabilities to perform those functions as well as limitations that limit performing the functions.

4. Development of Candidate Concepts

The identified functions at the different levels in the vertical dimension of the FDAM can be allocated to one of the systems (system elements) at the different levels in the horizontal dimension of the FDAM to create various concepts. Figure 5 shows the overall framework of the FDAM for ConOps development. A potential function allocation concept can be represented and analyzed using the two-dimensional FDAM.

Table 1 shows an example of how three categorizations of the separation assurance concept, which was represented in the concept map, can be created by allocating separation assurance functions at the system level of functional hierarchy to one of the subsystems of the NAS, such as ATCS or UAS.

By identifying potential function allocation decisions at the subsystem level, a wide range of combinations can be made. However, many of the potential concepts can be eliminated from further consideration because of technical or operational infeasibility or drawbacks. Therefore, it will be first process to select the subset of concepts that are deemed to have the highest potential for feasibility and acceptability. Currently there is no explicit method to select a set of plausible concepts. It can be typically selected by SME and the concept development team by considering operational capabilities and limitations. In this study, SME were consulted to provide feedback on the feasibility and acceptability of the function allocation; SME feedback often resulted in refinement to the functional decomposition, the function allocation, or both. Further, concept function allocation was reviewed with each concept iteration to refine the classification of the concept on the "level of automation" dimension. For example, if a given function allocation required a NAS capability that was not expected to be available until after 2025, the concept would be reclassified as representing a high level of automation, or the suitability/acceptability of the concept function allocation would be revisited. Those concepts that were deemed infeasible or unacceptable after multiple iterative refinements were either eliminated from consideration.

Table 1. An Example of Development of Concepts based on the Allocations of SA Control and Responsibility at the System Level.

Functions	Locus of SA Control and Responsibility		
	Controller-Provided UAS SA Concept	**Delegated UAS SA Concept**	**UAS-Provided Self Separation Concept**
F.1.1 Manage Strategic Separation Assurance of UA	ATCS and UAS	ATCS and UAS	UAS
F.1.1.1 Monitor and Evaluate Traffic Information for Strategic Separation Assurance	ATCS	ATCS	UAS
F.1.1.2 Predict/Detect Long-Term Conflicts of UA	ATCS	ATCS	UAS
F.1.1.3 Resolve Long-Term Conflicts of UA	ATCS	ATCS and UAS	UAS
F.1.1.4 Decide a Final Strategic Resolution Maneuver	ATCS	UAS	UAS
F.1.1.5 Issue Long-Term Conflict Resolution Maneuver to UAS	ATCS	N/A	N/A
F.1.1.6 Execute (Uplink) Long-term Resolution Maneuver	UAS	UAS	UAS
F.1.1.7 Manage UAS Flight Clearance Change Requests	ATCS and UAS	ATCS and UAS	ATCS and UAS
F.1.2 Manage Tactical Separation Assurance of UA	ATCS	ATCS and UAS	UAS
F.1.2.1 Monitor and Evaluate Traffic Information for Tactical Separation Assurance	ATCS	ATCS	UAS
F.1.2.2 Predict/Detect Short-Term Conflicts of UA	ATCS	ATCS	UAS
F.1.2.3 Resolve Short-Term Conflicts of UA	ATCS	UAS	UAS
F.1.2.4 Decide a Final Tactical Resolution Maneuver	ATCS	UAS	UAS
F.1.2.5 Issue Tactical Resolution Clearance to UAS	ATCS	N/A	N/A
F.1.2.6 Execute (Uplink) Short-term Resolution Maneuver	UAS	UAS	UAS
F.1.2.7 Monitor Compliance Status of Short-term Conflict Resolutions	ATCS	ATCS and UAS	UAS

The process of concept development employs recursion to refine conceptual elements as SME feedback is considered and function allocation is developed. To proceed with an analysis of those decisions, the functions at the level of subsystems need to be further decomposed into smaller functions so that we can apply a method that was proposed for guiding function allocation decisions, along with the consideration of several evaluative criteria, for types and levels of human interaction with automation. In the method, some recommendations about how to allocate functions between humans and automation were proposed based on human factors principles.[24]

C. Analysis of Potential Concepts using FDAM

Some concepts may require significant changes to existing ATC operating procedures to address UAS physical and performance characteristics in providing separation assurance services. The magnitude of required changes can be captured in the conceptual model of the concepts for separation assurance of UAS.

A set of standards and metrics including static and dynamic metrics was established and specified clearly to examine and evaluate the efficiency and validity of function allocation policies between humans and automation statically and dynamically.[24,33] Parasuraman et al. (2000) also provided a list of primary and secondary evaluative criteria for function allocation design in terms of human performance benefits and costs, automation reliability, and other metrics.[24] In this study, we have not investigated those metrics and not conducted any analysis to evaluate the trade-offs between potential concepts that can be generated through the FDAM framework. However, the conceptual representation of functional decomposition and allocation can be used to statically analyze the following metrics to address issues that may be considered in developing a concept of operations:

1) Stability Analysis: The FDAM can be used to identify functions performed redundantly by more than one system element. This stability analysis can be used to examine redundancy (or incompleteness) of the function allocation in the early concept development process by identifying situations where one function is allocated to two system elements. These incomplete functions should be decomposed into lower level functions until only one function is performed by only one of lowest-level system elements. This analysis can be used to examine whether there are any redundant functions in operating procedures.

2) Workflow Analysis: The FDAM also can be used to identify instances where a lower-level function is incorrectly allocated to another systems element. For example, if a function is allocated to UAS at the system-level functional hierarchy, all subfunctions of the function should be performed by one of UAS system elements. However, if any subfunction of the function is mistakenly allocated to other than UAS system elements, this is an incorrect function allocation. Therefore, this workflow analysis can be used to examine the incorrectness of function allocation in the early concept development process by identifying those situations.

3) Task Load Analysis: At the lowest level of the FDAM, the number of functions allocated to individual system elements can be used to measure the task load of the system element. The task-load balance across the system elements may then be evaluated for different concepts of operations in the early concept development phase. The task load of human elements can be used as a static workload measurement of human elements. For example, if there are too many tasks allocated to the human controller compared to other system elements, it may increase the controller's workload. In that case, it can be expected that shifting some functions to other humans or automation systems may reduce the controller's workload. However, the task load does not necessarily reflect the complexity and difficulty of the tasks. Thus, a detailed analysis on the workload and functional allocation performance should be conducted through human-in-the-loop simulations.

A computational modeling and simulation framework can be used to evaluate the performance and safety impacts of candidate operational concepts. Each of the primitive functions for individual system elements identified through the functional decomposition and allocation process can be used to model the corresponding agents of system elements and to simulate the interactions and dynamic behavior of those agents in order to evaluate the trade-offs among candidate concepts with a set of metrics using a fast-time simulation. Computational modeling and simulation will help identify the specifics and abnormalities of operational concepts and procedures. Operational concepts and procedures will need to be evaluated and appropriately modified through a fast-time simulation or human-in-the-loop simulation evaluation process.[24]

D. Application of Level of Automation for Desirable Function Allocation

The function allocation in the FDAM is basically an "all-or-none" approach in which a function can be allocated to either a human or automation. However, in most cases, it is not obvious whether a function should be allocated to automation or a human and to what extent, especially for functions that a human needs to perform by interacting with an automation system. The FDAM does not provide to what extent the identified functions should be automated, i.e. level of automation. Therefore, the most widely used framework for function allocation was applied as a supplement of the conceptual FDAM model in this study to clearly allocate the function between human and automation in terms of the scaled level of automation as shown in Table 2.[24]

At the system level of the hierarchy, it is difficult to identify a level of automation for functions assigned to individual systems since the functions at that level may involve more than one system elements. However, if a function involves an interaction between a human and automation at the component level of the hierarchy, we might be able to identify a desired LOA as recommended by the framework proposed by Parasuraman et al. (2000) rather than allocate the function to either fully manual (performed by a human) or fully autonomous (performed by a automation). As shown in table 2, if we allocate a function to automation instead of perform the function manually, then the LOA may vary from level 2 to level 10, based on the desired levels of interaction between a human and automation to improve overall system performance.

Table 2. Levels of Automation (Adapted from Parasuraman, Sheridan, & Wickens, 2000).

Level of Automation	Description
High (Fully Autonomous)	10. The computer decides everything, acts autonomously, ignoring the human
	9. Informs the human only if it, the computer, decides to
	8. Informs the human only if asked, or
	7. Executes automatically, then necessarily informs the human, and
	6. Allows the human a restricted time to veto before automatic execution, or
	5. Executes that suggestion if the human approves, or
	4. Suggests one alternative
	3. Narrows the selection down to a few, or
	2. The computer offers a complete set of decision/action alternatives
Low (Fully Manual)	1. The computer offers no assistance: human must take all decisions and actions

V. An Example of FDAM for ATCS-Provided Separation Assurance Concept

This example demonstrates how an ATCS-provided separation assurance concept in the NextGen timeframe can be constructed and analyzed using the FDAM framework as shown in Figure 6. The process starts from the top-left corner of the FDAM by allocating the top-level concept goal, “F.0 Provide Separation Management Service in En Route and Transition Airspace”, which is a goal of a concept of operation, to the level of the National Airspace System. As shown in Fig 4, the first-level functions, such as “F.1 Manage Separation between Unmanned Aircraft and All Other Aircraft” and “F.2 Provide Separation Services for Unmanned Aircraft to Avoid Other Hazards”, can be performed by both ATCS and UAS. The functions at this system level of the hierarchy may not be uniquely allocated to individual system elements at the next level in the horizontal dimension since all or some of the system elements interact with each other to accomplish the functions at the first level.

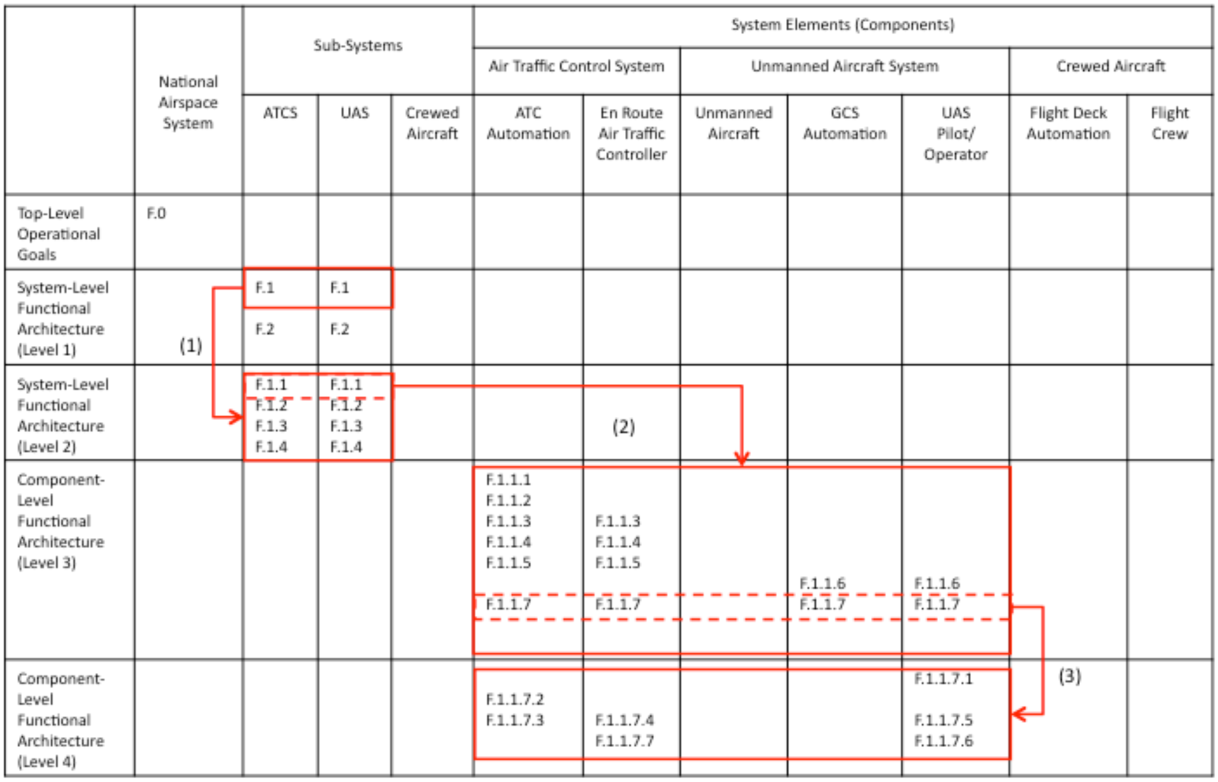

Figure 6. An Example of FDAM for an ATCS-Provided Separation Assurance Concept.

The second-level functions decomposed from the first-level functions (as shown in the Figure 4 and Table 1) can be allocated to one or more of the sub-systems based on available capabilities and technologies in the operating environment. The functional decomposition and allocation at the system level are represented in the FDAM as shown (1) in Figure 6. In this particular example, all second-level functions are allocated to both ATCS and UAS since the identified functions at this level are not sufficient to allocate to one of the system elements in the horizontal dimension. When the second-level functions are decomposed into the third-level functions, it should be considered whether the third-level functions can be allocated to one of the system elements. In our example, the second-level function, "F.1.1 Manage Strategic Separation Assurance of UA", is decomposed into seven different third-level functions and allocated into one or more of the system elements of ATCS and UAS as shown (2) in Figure 6. If a third-level function is allocated to just one of the system elements like F.1.1.1 and F.1.1.2, then these functions do not need to be further decomposed. However, if a third-level function is still performed by more than one system element (e.g., F.1.1.3, F.1.1.4, F.1.1.5, F.1.1.6, and F.1.1.7), then these functions should be decomposed into the next level because several system elements still interact to perform these functions. For example, as shown (3) in Fig. 6, the function at the third level, "F.1.1.7 Manage Flight Clearance Change Requests from UAS", is decomposed into seven different subfunctions, which are allocated to only one of the system elements uniquely. Therefore, the decomposition and allocation process for this function can be stopped at this level. As shown in Table 3, the component-level (level 4) functions are allocated to only one of the system elements, which means that the recursive decomposition process for this function can be stopped at this level.

Table 3. Component-Level Function Allocation Table.

Function	Functional Description	Primary Actor
F.1.1.7	Manage UAS Flight Clearance Change Requests	UAS and ATCS
F.1.1.7.1	Request Flight/Clearance Changes to ATC via data communication	UAS Operator
F.1.1.7.2	Evaluate UAS Operator's Request for Potential Conflicts	ATC Automation
F.1.1.7.3	Provide Probing Results of Requested Trajectory with	ATC Automation

	Advisories:	
F.1.1.7.4	Determine a response (Accept/Reject/Modify) and Send Response to UAS Pilot	Controller
F.1.1.7.5	Review ATC Response and Send Acknowledgment to ATC via voice or data communications	UAS Operator
F.1.1.7.6	Execute ATC Response: Uplink the Response to UAV if accepted	UAS Operator
F.1.1.7.7	Ensure ACK and Update the Host Computer with Issued Clearance/Instruction	Controller

A concept of separation assurance operations for UAS can be derived easily from the resulting FDAM representing which system elements should perform what functions at the different levels along with considering available capabilities and technologies. However, as described earlier, it is not trivial to allocate the component-level functions to just one of the system elements, especially if the function should be allocated between a human and automation. For example, as defined in Table 3, the component-level function "F.1.1.7.2 "Evaluate UAS Operator's Request for Potential Conflicts" can be allocated fully either to the controller or to ATC automation in a simple way. However, the "all-or-none" allocation approach might not be effective to improve overall performance of the system.[24] Therefore, it might be desirable to categorize those component-level functions into one of four function categories, such as information acquisition, information analysis, decision selection, and action implementation, and recommend a range of the levels of automation for those functions that involve the interactions between humans and automation as described earlier to concept developers and system designers. Appropriate selection of which system functions should be automated and to what extent is important in concept development and system design because the selected level of automation has a significant impact on the overall performance of the system.[22,24]

Table 4 was constructed to recommend a range of desirable levels of automation (LOA) for a delegated UAS separation assurance concept based on the recommendations from the previous research.[22,24] Since the required functions have been identified through the detailed functional decomposition and allocation analysis process, it is much easier to classify the identified function into one of four function categories and allocate the functions according to the recommended LOA. The recommended LOA can be used for further system design and requirements analysis in the design phase of system development.

Table 4. Function Allocation and Recommended Range of LOA for a Delegated SA Concept.

Functions	Primary Actor	Function Category	Recommended LOA
D.1.1 Delegate Responsibility to a UAS for Avoiding a Predicted Conflict with a Single Other Aircraft	UAS Operator	Action Implementation	1
D.1.1.1 Detect and Track All Aircraft Positions	ATC Automation	Information Acquisition	10
D.1.1.2 Monitor and Evaluate Future Trajectories of Traffic for Potential Separation Risks	ATC Automation	Information Analysis	7-10
D.1.1.3 Predict/Detect/Alert Conflicts of Unmanned Aircraft	Controller/ATC Automation	Information Analysis	1, 7-10
D.1.1.4 Evaluate a List of UAS Conflicts for Potential Delegation	ATC Automation	Information Analysis	7-10
D.1.1.5 Select a Pair of UAS Conflict for Delegating Resolution Responsibility to UAS Pilot	Controller/ATC Automation	Decision Selection	1, 3-8
D.1.1.6 Send Delegation	Controller/ATC	Action Implementation	1, 5-8

Notification to UAS Pilot via Voice/Data Communications	Automation		
D.1.1.7 Resolve the Predicted Conflicts of Delegated UAS with Single Other Aircraft	UAS Pilot/ GCS Automation	Decision Selection	1, 3-8
D.1.1.8 Decide a Final Resolution Maneuver for the Delegated UAS Conflict	UAS Pilot	Decision Selection	1
D.1.1.9 Communicate a Final Resolution Maneuver with ATC	Controller/UAS Pilot	Action Implementation	1
D.1.1.10 Transmit/Command a Final Resolution Maneuver to Unmanned Aircraft	UAS Pilot/ GCS Automation	Action Implementation	1, 5-8
D.1.1.11 Execute the Commanded Resolution Maneuver	Unmanned Aircraft	Action Implementation	10

VI. Concluding Remarks

This paper proposed a framework to develop separation assurance concepts for routine UAS operation in the NAS by identifying required functions from concept goals through a hierarchical functional analysis and allocating those functions to system elements based on a function allocation method in a structured and systematic way. This functional analysis framework will allow concept designers and developers to capture the relationships between integration goals and the detailed allocation of functions among key concept elements in the multi-dimensional concept map.

The two-dimensional FDAM developed as a test case in this study for ATCS-provided separation assurance concept demonstrated how the identified separation assurance functions for UAS through a hierarchical functional analysis can be allocated to individual system elements of the NAS at each level of the functional hierarchy. The additional analysis capabilities of this framework (i.e., stability analysis, workflow analysis, and task load analysis) help identify potential feasibility issues that a new function allocation decision would face in terms of task load, task balance, and number of interactions among primary system elements. Therefore, FDAM for another concept category, such as ATCS-UAS collaborative separation assurance or UAS self-separation category, can be constructed through the same process of the framework and then compared with one another in terms of stability, workflow, and task load.

In this study, a framework for levels of automation developed based on human factors and cognitive systems engineering principles was applied as a supplement method for clearly allocating identified functions to a system element, such as a human or automation, in terms of the scaled level of automation. This function allocation method may provide a better way to allocate the identified functions between human and automation with the different levels of automation rather than to allow a function to be performed only by either a human (fully manual) or automation (fully autonomous).

While the FDAM can identify some analytical issues apparent from representations of the functional relationships and allocations among system elements, many performance metrics need to be assessed over the course of time during simulations. Therefore, a computational framework for modeling and simulating the various SA concepts of operations represented in the FDAM needs to be developed to investigate the system-level complex and dynamic behaviors that cannot be adequately described in the conceptual models and how the results of the simulation can feed back to the conceptual models to improve and enhance the concepts. Dynamic fast-time simulations and human-in-the-loop simulations can be used to evaluate the relative strengths and weaknesses of various concepts and to identify operational conditions or situations under which the concepts can provide benefits or cause unacceptable safety or performance issues. Other systems engineering approaches (formal risk analysis and development of reliability, maintainability and availability (RMA) requirements) should be applied to lower the risk of transferring this technology to stakeholders. For example, risk analysis and performance requirements analysis should be conducted to investigate whether the potential concepts are implementable under the capabilities within a given timeframe and to examine what performance requirements are necessary to make the concepts achievable and acceptable.

Typically, a detailed and thorough analysis is required for the design and assessment of complex socio-technical systems in which individual system elements, including hardware, software, and human operators, interact with each other in a complex way to generate the overall behavior of the system. Therefore, it is expected that the functional analysis framework proposed in this study also will be applicable to the design and analysis of other complex socio-technical systems to represent the structural relationship among tasks and functions of system components and to evaluate the trade-offs among potential concepts of system design in a systematic way.

For future research, we are going to demonstrate how this approach can be applied to develop various UAS sense-and-avoid (SAA) operational concepts. A set of standards and metrics should also be developed to analyze the efficiency and feasibility of a wide range of concepts generated from the framework developed in this study. The understanding and insights about potential operations and function allocations gained through the functional decomposition and allocation process will enable more systematic trades between costs and benefits of a future concept.

Acknowledgments

The authors greatly appreciate reviewers; Paul Lee, Marcus Johnson, and Henry M. Sielski for providing thoughtful comments on an earlier version of this paper.

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