DISSERTATION

MBSAP APPLICATION TO UAV-BASED WILDFIRE DETECTION AND COMMUNICATION

Submitted by

Setrige W. Crawford

Department of Systems Engineering

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Doctoral Committee:

Advisor: Kamran Eftekhari Shahroudi

Mike Borky
Sonia Kreidenweis-Dandy
Thomas Bradley
Daniel Herber

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ABSTRACT

MBSAP APPLICATION TO UAV-BASED WILDFIRE DETECTION AND COMMUNICATION

By applying the concepts of the Model Based Systems Architecture Process [90] we were able to link stakeholder needs and operational scenarios (Use Cases) to the preliminary design validation of an autonomous hybrid electric/ gas turbine UAV (H-UAV) intended for wildfire detection and communication. The salient stakeholder requirements were captured, operational scenarios identified, trade study was completed, competing architectures were interlinked to a design exploration (DSE) and preliminary airframe sizing, where a user could probe the bounds of design variables in a probabilistic manner to reveal all necessary sensitives and confirm system behaviors were consistent with stakeholder requirements (spiral verification and validation).

This thesis takes the reader through this method and the development of each viewpoint, using Cameo Systems Modeler, starting with the Operational Viewpoint, then refinement to the Logical viewpoint and finally development of the Physical Viewpoint. Emphasized, is the use of a coupled architecture model (digital twin – virtual prototype) to confirm system behaviors against requirements and to graphically display system sensitivities. The deeper details of the DSE method and the trade study were previously published [119]. This paper focuses more on the MBSAP approach, the MBSE artifacts and reflects on the benefits of an interlinked model.[7]

The method developed affords the researcher a set of tools to efficiently converge on an affordable system solution which meets stakeholder needs and operational requirements

for a locally owned and operated wildfire detection and communication system. Further, the MBSAP method is systems agnostic in that. the approach, yields equally effective results whether applied to more software intensive systems, or more mechanical aerospace system (H-UAV) instantiations.

ACKNOWLEDGEMENTS

Golam Bokhtier (Aerospace Systems Engineer and PhD candidate at CSU) for discussions and brainstorming on the topic of big game changers related to flight dynamics and controls: i.e., the potential of using differential Fan-in-Wing with vectored thrust control to obsolete classical flight control surfaces and actuators, to gain significant improvements in range, survey time and $/(kg.km).

Barry Brinks (from Brinks Engineering) who created the 3D model of the H-UAV to provide feedback on initial design, sizing, and a baseline for future higher fidelity structural and aerodynamic optimization.

CSU PhD committee members Kamran Eftekhari Shahroudi, Mike Borky, Thomas Bradley, and Dan Herber for helping with the problem definition, brainstorming and problem solving, in addition to their normal duties of reviewing and examining the PhD research progress.

DEDICATION

I could not have completed this research and dissertation without the unwavering and unconditional support and love of my family. This dissertation is dedicated firstly to my incredibly supportive wife, best friend, and greatest critic Kym; to our kids: Setrige Jr.; Taisha; Tarin and finally, my dear Mother; Gloria. Thank you all.

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Introduction

Wildfires have been on the increase in frequency, duration, and intensity worldwide. Climate change, drought and other factors have not only increased the susceptibility to wildfires but have also led to increase the duration of the season. In the Western United States, wildfires can release as much carbon dioxide into the atmosphere in a week as all the automobiles in the region for an entire year [83][84].

Wildfires are detected much like they were 200 years ago, relying primarily on spotters in fire towers or on the ground and on reports from the public. This information is then augmented by aerial reconnaissance and lighting detectors that steer firefighters to the ground strikes, which are one of the more common wildfire sparks.

By applying the concepts of the Model Based Systems Architecture Process (MBSAP) [90] to this research, we were able to link stakeholders needs and operational scenarios (Use Cases) to the preliminary design validation of an autonomous hybrid electric/ gas turbine UAV (H-UAV) intended for wildfire detection and communication. The salient stakeholders' requirements were captured, operational scenarios identified, trade study was completed, competing architectures were interlinked to a design exploration (DSE) and preliminary airframe sizing, where a user could probe the bounds of design variables in a probabilistic manner to reveal all necessary sensitives and confirm system behaviors were consistent with stakeholders' requirements (spiral verification and validation).

This body of work takes the reader through this method and the development of each Viewpoint, using Cameo Systems Modeler, starting with the Operational Viewpoint, then refinement to the Logical Viewpoint and finally development of the Physical Viewpoint. Emphasized, is the use of a coupled architecture model (digital twin – virtual prototype) to confirm system behaviors against requirements and to graphically display system sensitivities. The deeper details of the MBSAP application, the DSE method and the trade study are captured in the preceding chapters.

The method developed affords the researcher a set of tools to efficiently converge on an affordable system solution which meets stakeholder needs and operational requirements for a locally owned and operated wildfire detection and communication system. Further, this research confirms that the MBSAP method is systems agnostic in that. the approach, which is normally applied to more software intensive systems, can be applied to more mechanical aerospace system (H-UAV) instantiations with equally effective results.

Research Questions

Research questions are as follows.

- What are the characteristics of an affordable aerospace platform that can meet the requirements for wildfire surveillance, detection, and communications application?
- What Propulsion Electrification strategies can be utilized on terrestrial platforms used to surveil, detect, and communicate the location of a wildfire?
- What are the critical mission segments that drive the overall system design methodologies for terrestrial platforms?
- What are the critical mission segments that drive the overall system design methodologies for a terrestrial fire detection and communication system?

- What are the benefits of applying a structure MBSE approach (MBSAP) to a less software intensive system such as a hybrid wildfire detection and communication?

Research Approach

The research is structured into three major sections; an application of the concepts of the Model Based Systems Architecture Process (MBSAP); a high-level Trade Study, where completing technologies were reviewed and merits confirmed; and finally, a Design Space Exploration, to identify sensitivities and the best design point.[90]

Modern system engineering techniques was used to anchor the trade study to ensure that we arrive at the best solution which meets the key requirements in a clear and methodological fashion with minimal subjectivity.

The overall strategy for the trade analysis is to break the study into six separate subsystems starting with a high-level trade, followed by a simulation/validation exercise, a re-examination of the system architecture, testing, risk analysis, and a brief discussion/possible application of cybersecurity onto the leading platform solution. We will distill necessary details for each subsection, with continuous validation of measures of effectiveness for the leading solution. The trade study will conclude with a final re-confirmation of the merits of the leading solution against an aggregate or alternative solution.[88][89][90]

The DSE approach integrates a particular analytical recipe of 18 Contributing Analyses (CA)'s together with solvers and constrained optimization routines to find the best design point. Once a design point is found, we wrap the above inside a Monte-Carlo loop to compare the relative advantages of UAV configurations (Electric versus Hybrid) in addition to finding the sensitivity of the design point to design drivers from operation, sizing, and technology measures.

A central tenet of MBSE is that the dimensions and behaviors of a system or system of systems can be captured by graphical and mathematical models. These graphical and mechanical models can serve as the foundation of the entire system engineering process, a Single Source of Technical Truth (SSTT) and further provides an explicit definition of the system.[90]

Model-Based System Architecture Process (MBSAP) is a specific implementation of the principles of MBSE with an emphasis on capturing and translating shake holder needs into effective and affordable systems solutions.[90]

With MBSAP as a forcing function, the research tasks completed were as follows.

- Requirements Assessment of an Affordable Wildfire Detection and Communications System.
- Trade Analysis using modern systems engineering techniques.
- UAV sizing method with an emphasis on hybrid electric propulsion systems.
- Demonstrate method / comparative analysis of similar system in industry.

Research Contributions

The Research Contributions are as follows.

- Trade study of different platforms used for wildfire detection and communication leading to a new understanding of the benefits of proactive vs reactive mitigation strategies.

- Scholarly review of current UAV literature leading to new understanding of hybrid electric propulsion system / UAV aerodynamic synthesis.
- Developed a new method for sizing UAV Hybrid Electric propulsion systems.
- A coupled reference architecture for a Hybrid UAV using MATLAB simulation / validation and At-Risk simulation / validation.
- Scholarly review and development of simulation and validation methodologies for transitional UAV hybrid electric propulsion UAV systems.
- Review of energy storage technologies and applications to UAV systems.
- Review of Electric Motor Technologies and applications to UAV systems.
- Review of small turbine engine technology and applications to UAV systems.
- Review of several multidisciplinary relationships needed for Design Space Exploration.
- Review of MBSAP with focus on UAV architecture to inform understand mission requirements / mission operational needs to requirements.
- Simulation based understanding of impact of major technology trend on the development of a parametric executable model to be used for Design Exploration
- Identification of significant design space for UAV application for wildfire detection and communication.

Wildfire Background

Wildfires have been on the increase in frequency, duration, and intensity worldwide. Climate change, drought and other factors have not only increased the susceptibility to wildfires but have also led to increase the duration of the season. In the Western United States, wildfires can release as much carbon dioxide into the atmosphere in a week as all the automobiles in the region for an entire year.[84][97][98] A key study estimates that fires in the contiguous United States and Alaska release about 4 to 6% of the nation greenhouse gases released through burning fossil fuel or about 290 million metric tons of carbon dioxide a year.[98]

In 2021 there were 58,985 wildfires that burned 7,125,643 acres. The total number of fires and acres burned in 2021 were like both the five year and ten-year national averages, however, 2021 was a notably active year for certain Geographic Areas. 2018 was the deadliest and most destructive on record in California. Some 8527 fires burning an area of 1,893,913 acres which was the largest amount of acreage recorded in a fire season. The fires have caused more than USD 3.5B in damage including USD 1,792 M in fire suppression costs. Cal Fire alone spent USD 432 M on operations**.** [93][98]

Today, wildfires are detected much like they were 200 years ago, relying primarily on spotters in fire towers or on the ground and on reports from the public. This information is then augmented by aerial reconnaissance and lighting detectors that steer firefighters to the ground strikes, which are one of the more common wildfires sparks.

According to the National Park Service, a staggering 85% of wildfires are human caused, while lightning strikes account for about 10% of wildland fire. Human-caused fires result from campfires left unattended, the burning of debris, equipment use and malfunctions, negligently discarded cigarettes, and intentional acts of arson.

UAV technology assists in the reduced time for detection of wildfires and is especially helpful in the estimation of the amount of vegetative fuel and climate measurements that can influence and affect the intensity, direction, and potential devastative effects of wildfire. Clearly, in wildfire-prone areas, UAV technology is a suitable addition to the arsenal of wildfire detection and suppression.

The goal of this body of work is to present the reader with a MBSAP implementation for a UAV system instantiation for wildfire detection and communication. Also provided in this work are systems engineering models and artifacts which can be used as design patterns for local UAV fire detection and communication systems.

Chapter 2
MBSAP – Application for Wildfire Detection and Communication
MBSAP Method

Model-Based System Architecture Process (MBSAP) is a specific implementation of the principles of MBSE with an emphasis on capturing and translating shake holder needs into effective and affordable systems solutions.[90] For the H-UAV application, the approach is based on using a high-level system architecture as the foundation for objective, quantification, sizing, and analysis of the system performance. In line with the accepted practices of contemporary systems engineering, those aspects of the H-UAV systems performance which are important to the stakeholders, are captured using viewpoints (Operational, Logical/Functional, Physical). Viewpoints and their specific contents to inform the architectural building blocks for the H-UAV system to be instantiated. Reference Figure 1

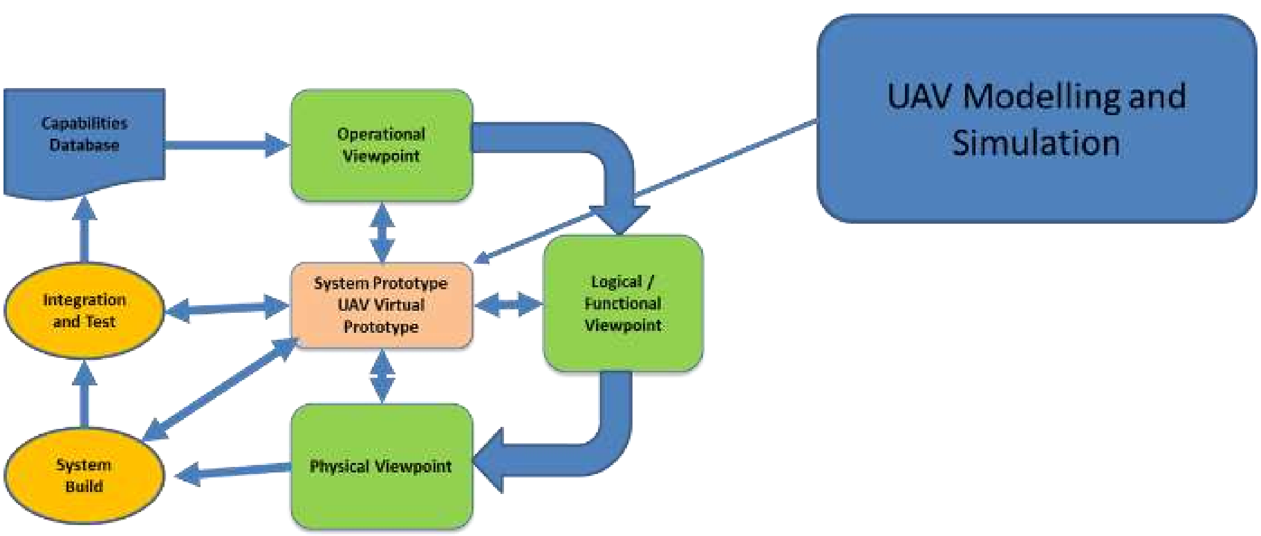

Figure 1: Operation Viewpoint (OV)

Operational Viewpoint

The first step of H-UAV MBSAP Operational Viewpoint (OV) is to transform stakeholders' requirements, however expressed, into an architectural context, using several artifacts (UCs, Scenarios, Needs Analysis; ADs, BDD, IBD, CDM etc.).

This process and the resulting artifacts, creates a foundation for system design, and as such, sufficient attention, is essential to avoid inconsistencies from cropping up later in the development cycle as further system details are fleshed out in the Logical Viewpoint (LV) and Physical Viewpoint (PV). As the OV is developed, these artifacts are subjected to rigorous analysis to resolve issues, to provide a high-quality basis for an effective and affordable solution, and to establish a common reference point for the various engineering functions involved in developing the H-UAV. The OV is therefore a key tool for dialog with the customer and other shareholders, to shape the system design and communicate the features and operational behaviors of the evolving system solution. Reference Figure 2

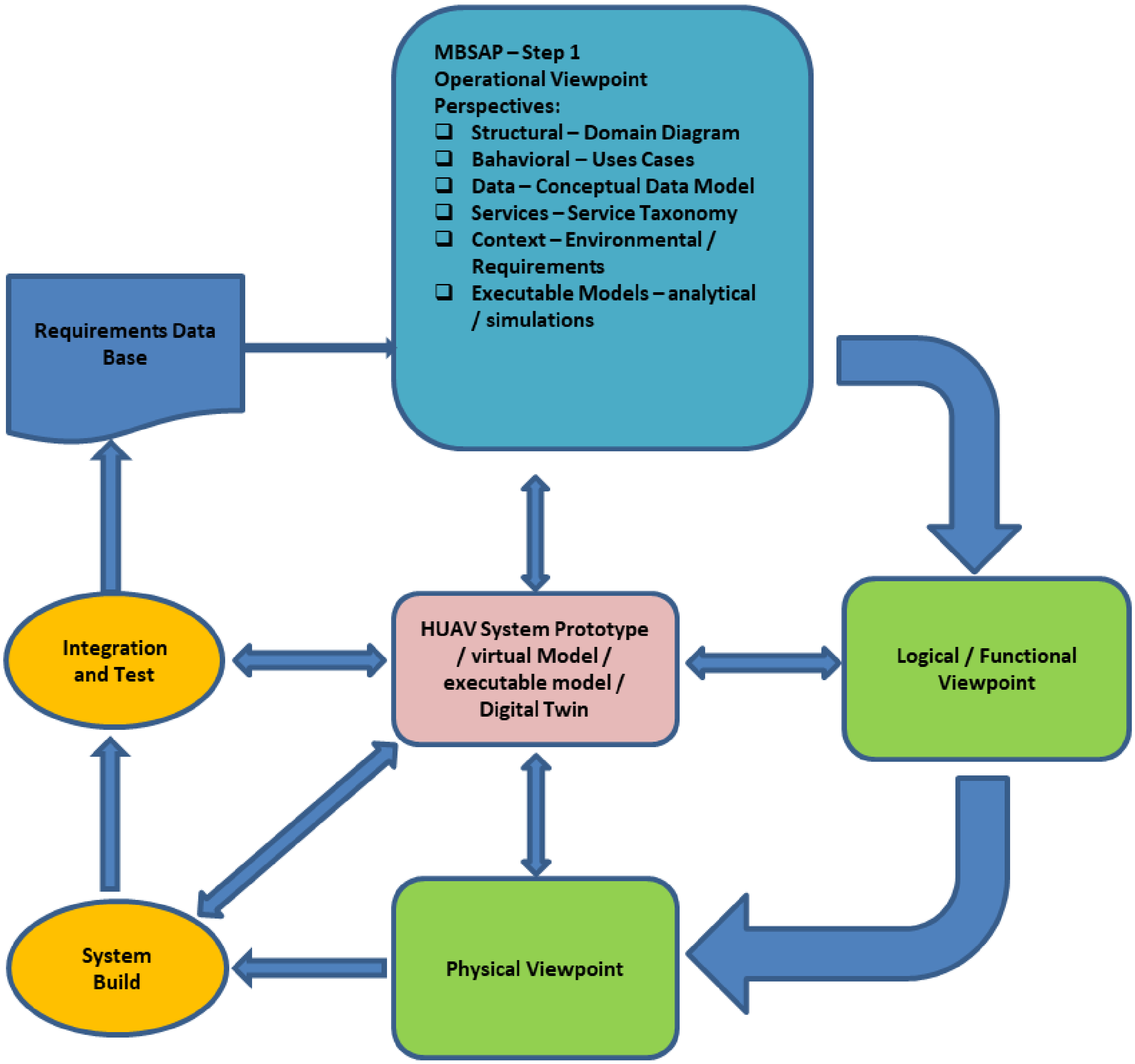

Figure 2: OV Process Summary

Trade Analysis Summary

The overall strategy for the trade analysis is to break the study into six separate subsystems starting with a high-level trade, followed by a simulation/validation exercise, a re-examination of the system architecture, testing, risk analysis, and a brief discussion/possible application of cybersecurity onto the leading platform solution. We will distill necessary details for each subsystem, with continuous validation of measures of effectiveness for the leading solution. The trade study will conclude with a final re-confirmation of the merits of the leading solution against an aggregate or alternative solution [6][7][25]. The reader is encouraged to reference the trade analysis paper and chapter three, reference here for a full accounting of the subsystems traded. For this body of work, the over-arching goal is to use an MBSE approach to drive the necessary systems engineering rigor into the optimization and validations for the leading concept, a transitional UAV with hybrid electric propulsion system.[6][7][25][48] Numerous models and artifact were developed as part of the MBSAP. Of significant, is the executable model or digital twin, which was developed and used for continuous validating, design exploration and sensitivity analyses.[34][35][36][37]

Logical / Functional Viewpoint (LV)

The H-UAV LV is developed by parsing and fleshing out details to the five perspectives of the OV. The LV, for this application was kept independent of any technologies or products and represents a functional definition of the fire detection and communication enterprise and in particular the H-UAV subsystem within that enterprise.

In the H-UAV LV, discrete design parameter options are still abstract. Or at least there are ranges defined but not yet optimized for the primary behaviors. The next step in MBSAP, PV – is where further details are added to the executable model, used for analyses and documentation of the components that instantiate the Blocks from the LV. System components or digital representation of those components are typically a mix of intervention (newly developed or modified) and off-the-shelf (leverage) products and or design philosophies proven to be effective in other applications. Components like the turbine ICE, EM and vector nozzles are such examples for this application. Reference Figure 3

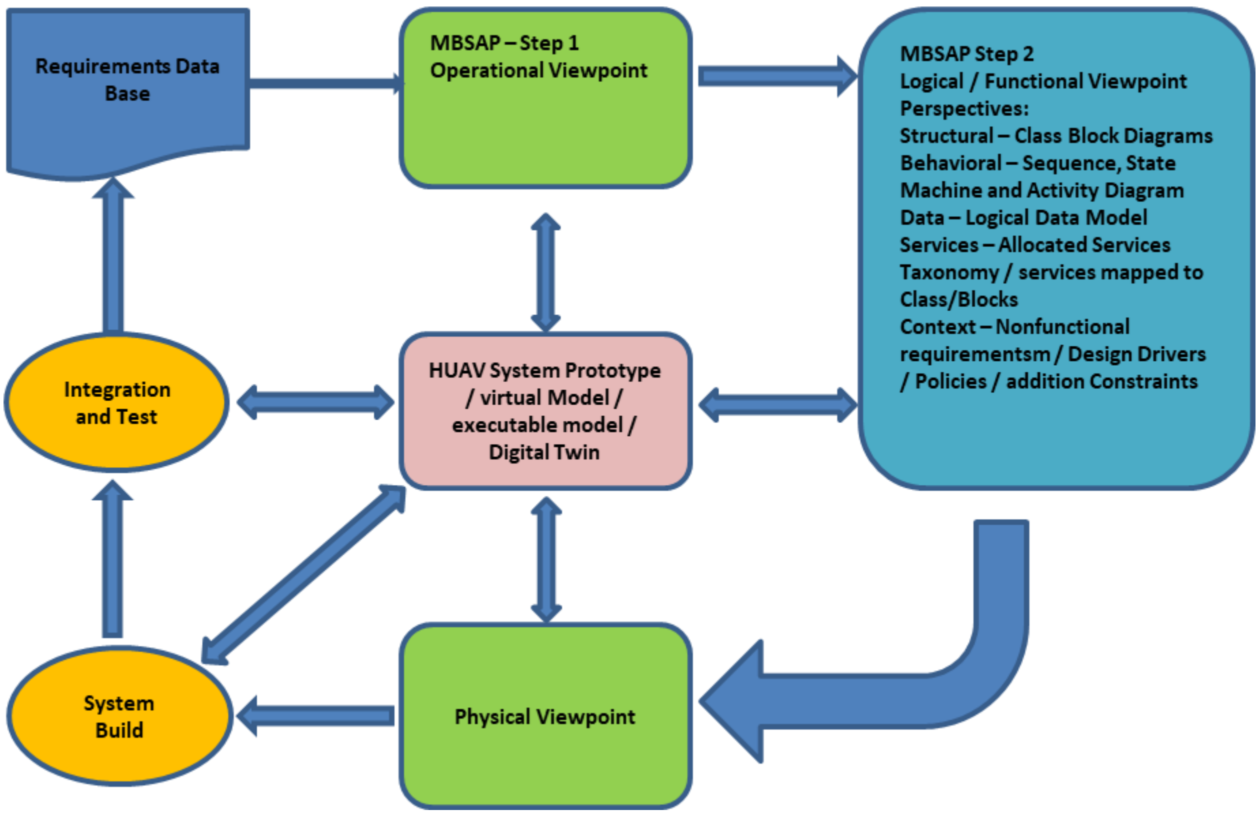

Figure 3: LV Process Summary

Physical Viewpoint (PV)

The third and final step in the MBSAP procedure is completed by mapping the LV to the PV, which is then the basis for the implementation of an increment of capabilities in the executable model (digital twin). Benefits of using an executable model in lieu of a physical prototype are more cost effectiveness and greater degree of exploration of key design parameters.

In the PV, MBSAP combines the Structural and Behavioral Perspectives of the OV and LV into a H-UAV Design Perspective to reflect emphasis on the most important subsystems components. Reference Figure 4

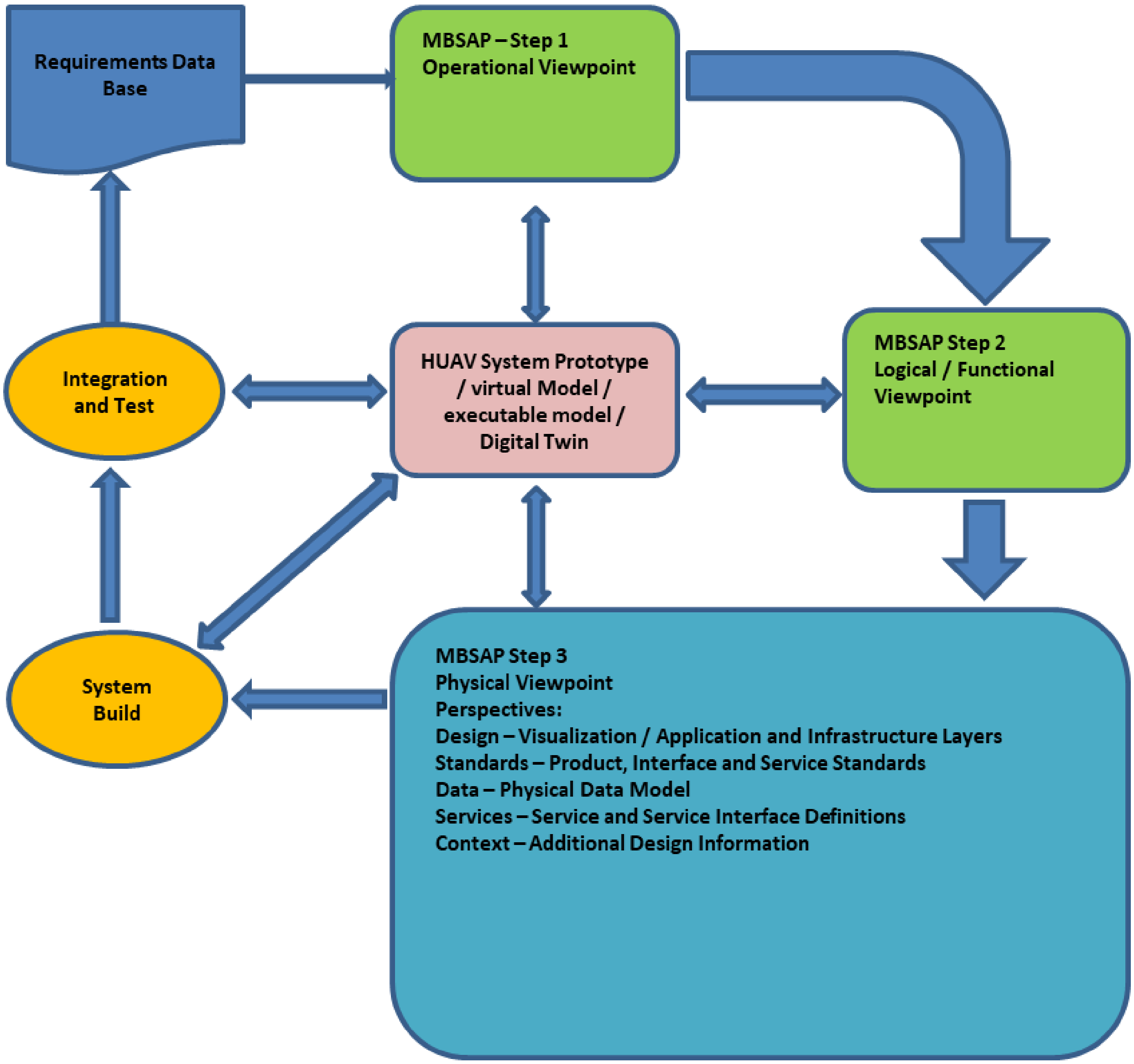

Figure 4: PV Process Summary

Viewpoint Summary

In the Operational Viewpoint, an architectural foundation is instantiated which is the leap from the customer requirements and desires to a formal, analyzable context. Figures 5-18 summarize the content of the OV. Earlier in the discussion, it was noted that architecture is about managing complexity, and the first step is to frame that complexity in a modeling environment that can account for critical system behaviors. Figure 25 is a summary view of the H-UAV modelling architecture and allows designers to attack the right problems in the right order, supported by analysis and traceability.[39] The OV provides a top-level functional structure of the enterprise and/or system, the behaviors of each functional area and the enterprise or system as a whole exhibit, and a start on defining information content and services. This stage of MBSAP also brings along an updated requirements database with flow-down and allocation of requirements that are appropriate to the level of decomposition the OV reaches. Reference Tables 2 and 3, Figures 8 and 9.

In the Logical Viewpoint, the H-UAV architecture has matured to a point where, results of modelling and simulation can inform the efficacy of the functional design. The H-UAV Structure is defined down to Blocks, behaviors of individual Blocks and Block collaborations. LV development has also validated the kinds of layered SOAs that are appropriate to system performance categories, to meet the needs of the Wildfire Detecting and Communicating (FD&C) H-UAV system.

The system artifacts which were fleshed out in the LV, summarized in Figure 3, inform design requirements and specifications for the H-UAV system implementation in the final Viewpoint (Physical Viewpoint).

In the Physical Viewpoint, the fundamental architecture development is completed, and H-UAV design baseline is captured, upon which simulations is completed to continue the incremental verification and validations. Reference Figure 25 through 29 for Viewpoint artifact which capture the H-UAV instantiation in the form of a coupled architecture or digital twin. Also captured are considerations for how the system will be used throughout its useful life and equally important, how the system might evolve to satisfy different and changing initial services. Further, a robust architecture, built on the principles of MBSAP and substantiated by the necessary viewpoint artifacts enables continued effectiveness, supportability, and affordability, as operational environments change, and or technologies change.

Viewpoint Perspectives Artifacts

Viewpoint Perspectives and Artifacts are normally instantiated in the first Viewpoint and iterated or fleshed out as MSAP moves through successive viewpoints, however, in this body of work, they will be presented is summary. The reader is encouraged to review material by Borky et al [90][92][99][100][101][102] for a more detailed handling of the referenced topics.

Service Perspective

The wildfire detection and communication system services are set up to be more functional and intuitive so that a perspective client does not need to know exactly where or what node in the system to direct the service request to. The request is simply directed to a common enterprise node and a response is formulated regardless of where the data resides or if data must be generated. For example, if the service request is for area surveillance already captured in the base station data base, then the service request can by satisfied without calling up the H-UAV operations. On the other hand, if there is no data for the service request area of interest, then the H-UAV operation will be called up and the behavior necessary to satisfy the service request is initiated. Reference Figure 5 and Table 1

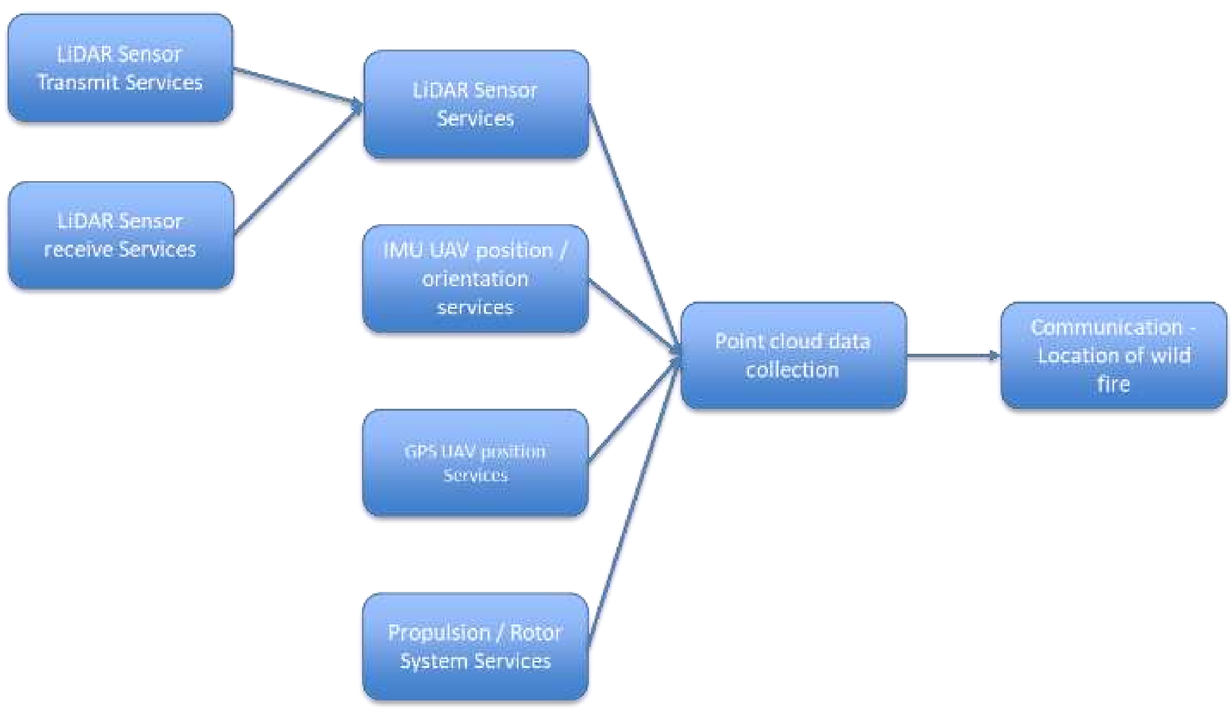

Figure 5: PV Additional H-UAV Service Details

Table 1: LV Services

System Service	Use Cases	Domains	Domain Sevices	Subdomains	Classes/Blocks	Operations
Perform LiDAR surveillance of area of interest Generate point cloud data, update and manage flight track	Perform Sensing	FS Management	Control LiDAR Sensor	Sensor Resource Management	Collection TaskQueue	GetTask() UpdateTaskQueue() CreateTask()
		Control Sensor		Sensor Resource Management	Task Queue	Get(Task) UpdateTaskQueue() Create Task()
					Sensor Characteristics	GetAllocated(Sensor) GetResourceStatus ReportResourceCapabilities()
					Constraint Manager	GetExternalConstraints() GetResourceCapabilities() ReportResourceCapabilities()
					Service Area Request	GetResourceTask() CreateSensorServiceRequest() SendSensorServiceRequest()
					LiDAR Data Reports	GetFSStatus() ReportFSStatus()
			Process Sensor Report	Sensor Product Development	Sensor Data Processing	GetSensorData() ProcessSensorData() SendSensorData()
					Sensor Report Processing	GetProcessData() CreateSensorReort() SendSensorReort()
				Sensor Information Management	Sensor Information Processing	GetSensorReport() PublishSensorReort() UpdateSensorDataBase()
			Generate Flight Track Report	Sensor Product Development	Sensor Report Processing	CreateTrackReport() SendTrackReort()
Perform Flight Path Control	Navigate UAV	Flight Path Management	Control Flight Path	Flight Control Resource Mgmt	IMU	GetInertialData() ProcessInertialData() SendInertialData()
					GPS	GetGPSData() SendGPSData()
					AHRS	GetInertialData() ProcessInertialData() SendInertialData()
					Autopilot	GetfltData() GetGPSData() GetEngData() ProcessData() CommandFltEngControl
			Control Propulsion	Propulsion Control Resources Mgmt	Engine Instrumentation System	GetengparameterData() ProcessData() SendData()
					Electronic Throttle Control ECU	GetEISData() ProcessEISData() SendEngControlData()
			Traffic Avoidance	Navigation Resource Mgmt	ADSB receiver	GetADSBData() ProcessADSBData() SendADSBData()
					GPS-WAAS	GetGPSWAASData() ProcessGPSWAASData() SendGPSWAASData()
					Nav Module	GetNavData() ProcessNavData() SendNavData()

Needs Analysis

The main purpose of this phase of the MBSAP method is to objectively define the operational needs for the system to be instantiated and that there is an approach for fulfilling the needs at an affordable cost within an acceptable risk profile. The analysis addresses the question of whether a system is needed and can offer a clear improvement in capabilities over existing systems. To achieve this, there should be at least one or two concepts and or executable models which can show functional capabilities and or behaviors, consistent with basic requirements. Outputs should be convincing enough to persuade major shake-holders that the system is feasible and can be developed and produced within cost constraints and at an acceptable risk level.[90] The needs analysis is a cyclic process beginning at or about the concept phase of the system engineering life cycle and continuing through the development and detail design phases to close with feasibility and need validation. There are four basis subparts to a needs analysis. Operational Analysis – where the needs for the new system are understood; Functional Analysis – where functions and behaviors are defined to conduct operations; Feasibility Definition – where the approach to be instantiated is visualized with various models; and finally, Needs Validation – where the “Cost Objectives” are validated.

FD&C H-UAV Functional Requirements

FRs, especially for H-UAV systems, commonly have defined quantitative values. These commonly include Thresholds and Objectives that are, mandatory and desired levels of performance. These values become criteria for the H-UAV system incremental verification using executable models during the initial stages of development. Results of these initial tests and analyses are used to assess system performance and the ability of the architecture to support the required performance levels. Reference Figure 6 and Table 2

Table 2: Functional Requirements

#	Name	Text
1	3 HUAV Specification	
2	3.1 HUAV Functional Requ	High-Level Functional Requirements (FR) of the Wildfire UAV at the enterprise level has been captured in this section.
3	3.1.10 HUAV Informati	UAV Information Management Requirement
4	3.1.10.2 IM-2	The system shall provide mission data storage, access and communication to a base station.
5	3.1.10.1 IM-1	The system shall implement cybersecurity at multiple classified levels.
6	3.1.9 HUAV Mass	UAV Mass
7	3.1.9.1 HAUV Mass	The UAV maximum weight mass (Maximum Take off weight) shall be 45 Kg or less.
8	3.1.6.1.3 HUAV	The maximum fuel capacity shall be 15 Kg (STD).
9	3.1.6.1.2 HUAV	The UAV BUS structure maximum weight shall be 20Kg or less.
10	3.1.6.1.1 HUAV	The UAV maximum payload mass shall be 10Kg or less.
11	3.1.8 HUAV Flight Ope	UAV Flight
12	3.1.8.3 Flight Op-3	The system shall allow remote flight crew to respond to dynamic mission requirement and flight conditions.
13	3.1.8.2 Flight Op-2	The system shall enable mission plan execution.
14	3.1.8.1 Flight Op-1	The system shall perform pilotage and navigation for safe aircraft operations.
15	3.1.7 HUAV Mission Ma	UAV Mission Management
16	3.1.7.1	The system shall perform preflight mission planning and in-flight dynamic replanning as commanded or as scheduled.
17	3.1.6 HUAV Dash Spee	UAV Dash Speed
18	3.1.6.1	The UAV shall have a minimum dash speed of 125 Kph IAS (Indicated Airspeed) or greater.
19	3.1.5 HUAV Endurance	UAV Endurance
20	3.1.5.1 Endurance	The UAV shall have a minimum endurance of 3 hours, inclusive of launch, climb, dash, loiter and landing phases of flight.
21	3.1.5.1.1	The UAV shall have a minimum fuel reserve of 10% of the baseline mission requirements.
22	3.1.4 HUAV Communic	UAV Communications and Networking
23	3.1.4.2 Communica	The system shall implement integrated onboard and off-board networking.
24	3.1.4.1 Communica	The system shall provide health information of the Flight Control Systems and subsystems to the Base Station (BS) via the communication systems of the aircraft.
25	3.1.3 HUAV Sensor Ex	UAV Sensor Exploitation
26	3.1.3.2	The sysem shall perform tracking, geolocation and identification of wildfires.
27	3.1.3.1	The system shall manager and update flight path tracks.
28	3.1.2 HUAV Loiter Spe	UAV Loiter Speed
29	3.1.2.1	The UAV shall maintain a minimum loiter speed of 100 Kph IAS (Indicated Airspeed) or greater.
30	3.1.1 HUAV Detection	UAV Detection
31	3.1.1.3 Wildfire Siz	The wildfire detectable size shall be 3 meters or greater.
32	3.1.1.2 Detection L	The wildfire location shall be reported as GPS latitude/longitude with an accuracy of +/- 3 meters.
33	3.1.1.1 Detection T	The UAV system shall detect the location and size of a wildfire in 4 hours or less from the time the wildfire is started.

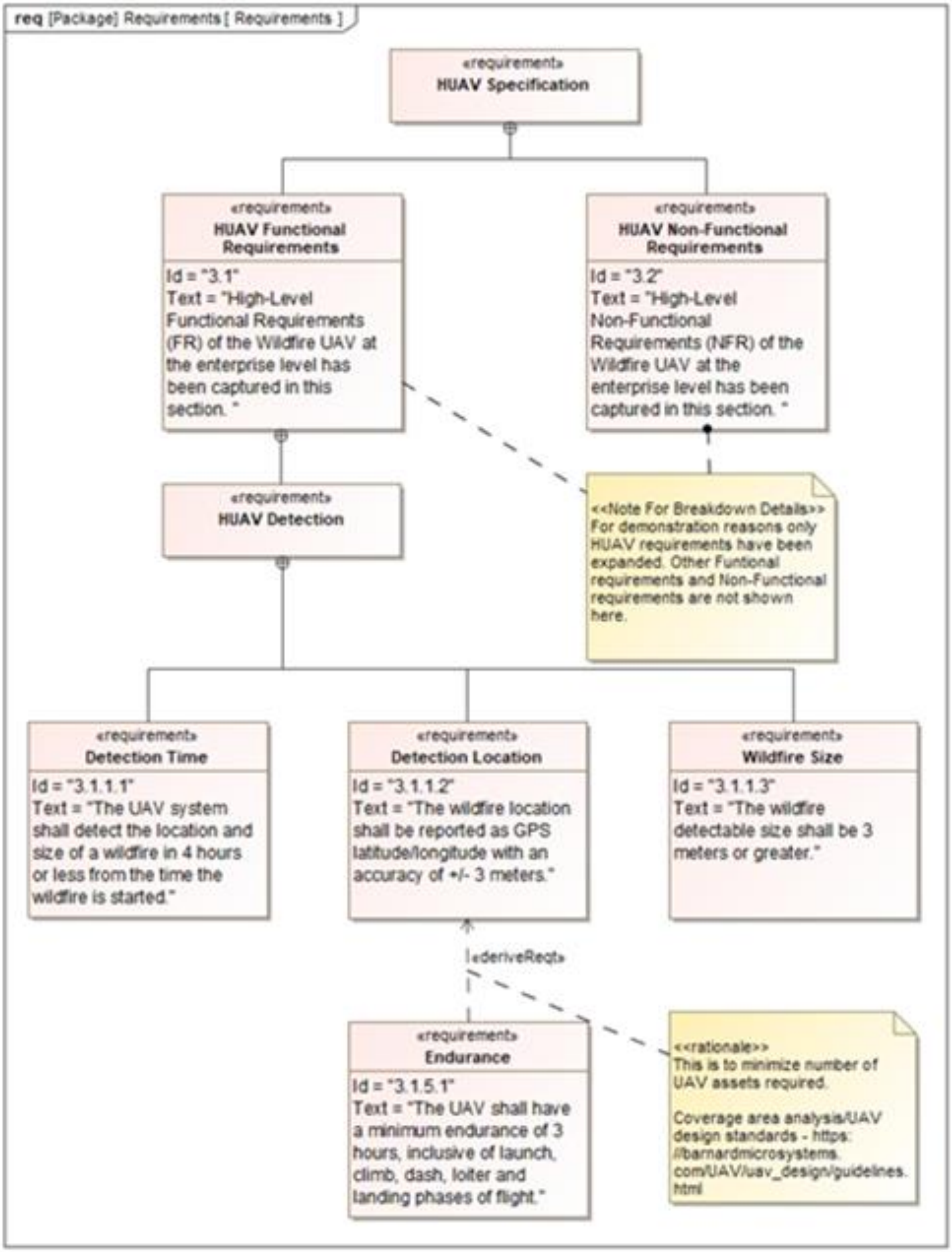

Figure 6: Functional Requirements

FD&C H-UAV Non-Functional Requirements

Non-Functional Requirements (NFR) for the H-UAV represent non quantifiable key concerns of various stakeholders. Using H-VAU as an example, typical NFRs deal with overall aspects of the system such as reliability, maintainability, and availability (RMA); environment tolerance; safety; security; and policy compliance, especially with respect to open architecture. See Table 3**.**

Table 3: Non-Functional Requirements

#	Name	Text
34	3.2 HUAV Non-Functional	High-Level Non-Functional Requirements (NFR) of the Wildfire UAV at the enterprise level has been captured in this section.
35	3.2.7 HUAV Supportab	UAV Supportability
36	3.2.7.1	The system shall satisfy RMA requirements in the prescribed operational environment with minimal Special Test Equipment (STE) and other external support.
37	3.2.3 HUAV Safety	UAV Safety
38	3.2.3.1	The system shall achieve required DO-178C and DO-254 certifications.
39	3.2.3.2	The system shall implement prescribed safety standards, policies and directives.
40	3.2.6 HUAV Network C	UAV Network Capability
41	3.2.6.1	The system shall conform to enterprise services, protocols and interfaces
42	3.2.2 HUAV Cybersecu	UAV Cybersecurity
43	3.2.2.1	The system shall implement Confidentiality, INtegrity, Avilability and other security attributes in accordance with approved Security plan.
44	3.2.2.2	The system shall be able to autonomously return to Base Station in the event of a credible hacking attempt.
45	3.2.2.3	The sstem shall be able to prevent receive communications in the event of a credible hacking attempt.
46	3.2.1 HUAV Availability	UAV Availability
47	3.2.1.1	The UAV system shall have a minimum avilability of 90%.
48	3.2.4 HUAV Affordabili	UAV Affordability
49	3.2.4.3	The UAV system retirement cost shall be $100K or less as measured in 2023 dollars.
50	3.2.4.2	The UAV power plant shall have an MTBO of 2000 hours or greater.
51	3.2.4.1	The total operating budget for the UAV shall be 5% or less of the CA operating budget in 2023 dollars.
52	3.2.4.4	The maximum yearly operations cost shall be $1.9M or less measured in 2023 dollars.
53	3.2.8 HUAV Deploymer	UAV Deployment Flexibility
54	3.2.8.1	The UAV shall have the capability to take off and land from unimproved or remote locations.
55	3.2.8.2	The UAV shall attain flight without a horizontal ground run mode.
56	3.2.8.3	The UAV shall complete land mode without a horizontal ground run mode.
57	3.2.8.4	The UAV shall be capable of operations in IMC.

-

Domain Specification – UAV BUS

The H-UAV Domain Specifications includes amongst other artifacts and elements, drawings and diagrams which are the beginning of the development of an architecture model. Development of Domain Specifications can be initially time consuming but yield appreciable benefits in the long run by promoting structures that are completely understood, consistent with each other, and easy to communicate to all stakeholders including, customers and system developers. Typical Domain specifications include the following; Owner – identification of the organization or individual(s) who have to approve the23definition of the Domain and its specification; Description: a summary statement purpose and functions; Definitions: any terms additional context required to add understanding to the Domain; Operations: behaviors the Domain produces, which are best divided into externally observable operations and internal operations; Data: a listing of the primary data entities which are either inputs or outputs and are usually collected in the Conceptual Data Model, discussed later in this chapter; Interfaces: a listing of the external and internal (inter-Domain) interfaces created or used by the Domain; Allocated Requirements: once requirements are mapped to the Operational Viewpoint, each Domain specification tabulates the FRs which are to be satisfied in whole or in part by that Domain and the NFRs that impact the Domain and must be addressed in its implementation. See Figures 7 and 8. For examples of a domain specification for the H-UAV.

UAV Climb and InFlight Checks

Owner: System Developer
General Description: UAV autonomously perform climb flight checks
Precondition: UAV launched Direct Launch or Mobile Launch
Trigger: UAV Take Off and Climb
Postconditions: UAV enter Dash portion of flight
User Roles: determine which scenario to conduct - primary or secondary scenario
Data Objects: system parameters / battery power / propulsion / sensor / loiter fuel
Primary Scenario: UAV perform climb flight checks – and continues to Dash portion of flight
Secondary Scenario(s): UAV performs climb flight checks and determine that there is a fault with sensor or flight systems and returns to mobile or Primary Base Station
Allocated Requirements:
R-F-112

Figure 7: Domain Specification – H-UAV Climb and Inflight Checks

Conduct Post Flight System Checks

Owner: System Developer
General Description: Maintenance resources perform UAV systems checks
Precondition: UAV returns to base station
Trigger: UAV returns to base station after successful data collection or if climb flight checks finds fault
Postconditions: UAV routed to repair or ready for flight station
User Roles: determine flight readiness of UAV
Data Objects: system parameters / power / propulsion / sensor
Primary Scenario: UAV completes post flight checks successfully and returns to ready for flight station
Secondary Scenario(s): UAV completes post flight checks and fault is discovered – UAV routed to repair station
Allocated Requirements:
R-F-111

Figure 8: Domain Specification – H-UAV Post Flight Checks

Structural Perspective

The H-UAV OV and LV are partitioned into their fundamental Perspectives (Structural, Behavioral, Data, Services and Contextual Perspectives), however, there is interaction between these perspective until a reasonable representation is fleshed out as an output of the OV. Reference Figures 9 and 10. The perspective has natural dividers and for the H-UAV, those natural boundaries were, the remote base station or truck, the UAV itself and the home base station where data reduction and other UAV preparations and maintenance activities are to be conducted. The H-UAV can be further partitioned into its major functional elements such as the BUS systems and Payload subsystems. The BUS system is described in further details in chapter 4 page 127..Another fundamental aspect of the structural perspective is that its organization takes into consideration, where data is captured, reduced, stored, and used and how it is communicated among functional areas and with the external environment..

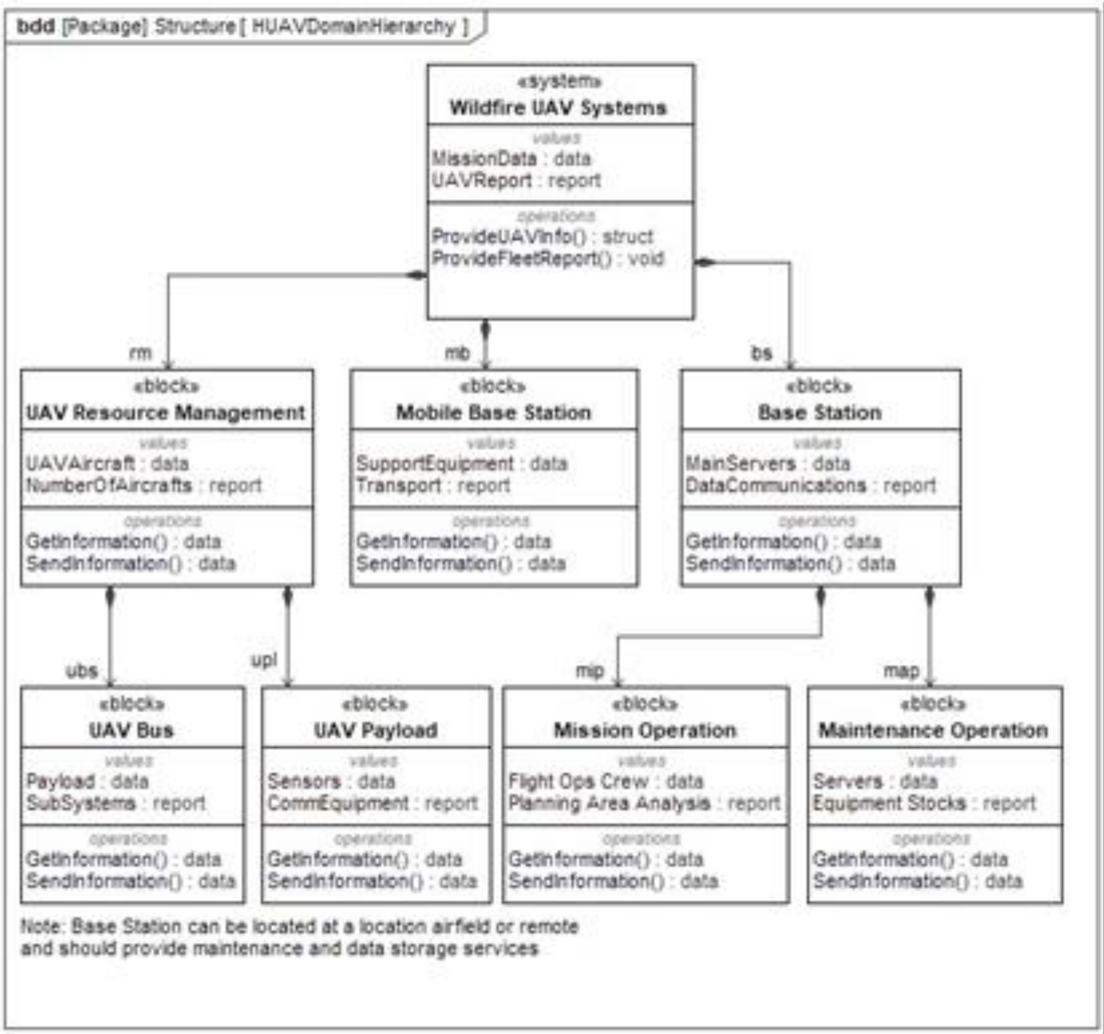

Figure 9: Fire Detection and Communication System Block Definition Diagram

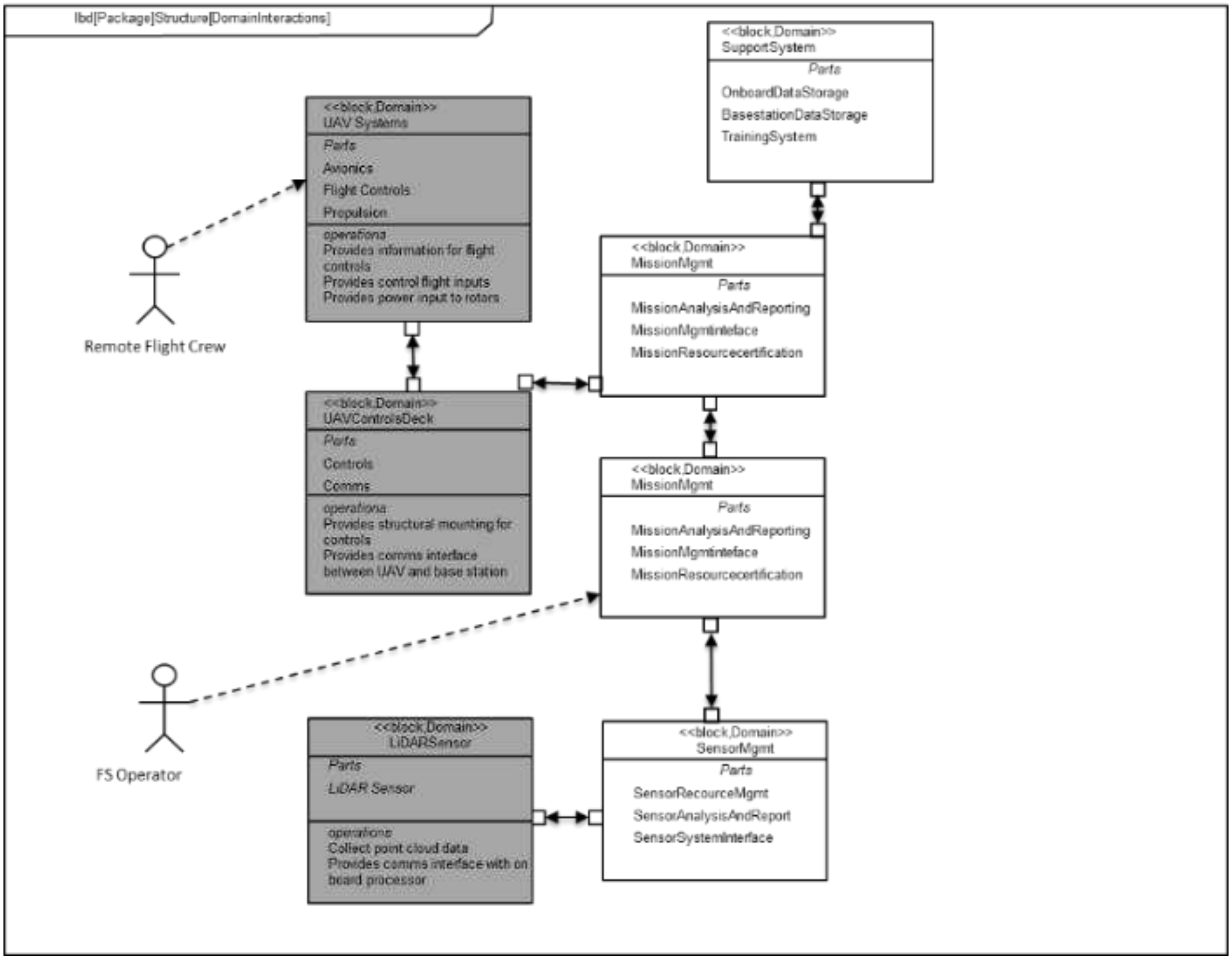

Figure 10: Logical Viewpoint - IBD

Behavioral Perspective

As noted previously, development of the H-UAV perspectives occurs in parallel and is an iterative process, in the OV and LV, until the natural sequence of events can be graphically represented. The Structural Perspective, however, is closely related to and is complemented by the Behavioral Perspective, which represents the behaviors displayed by the system and its Domains. Reference Figure 13 for a typical fire detection and communication UC with the starting point being a mission request. High level behaviors across multiple domains are captured and further distilled to exposure the UAV behaviors required to complete the mission. These behaviors will serve as the foundation for the executable model which will be used for initial sizing and verification / validation.

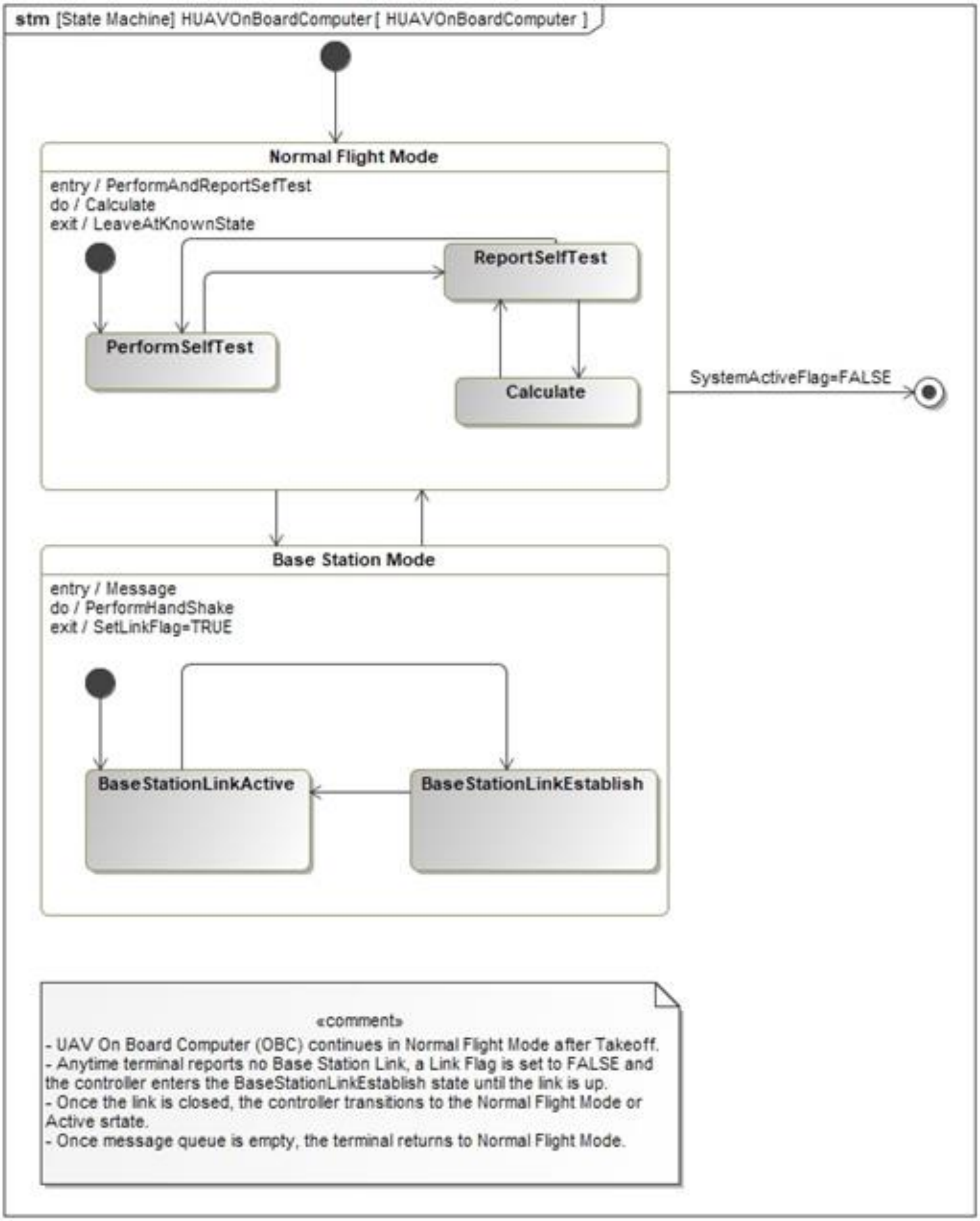

Figure 11: LV Stateful Behaviors – STM

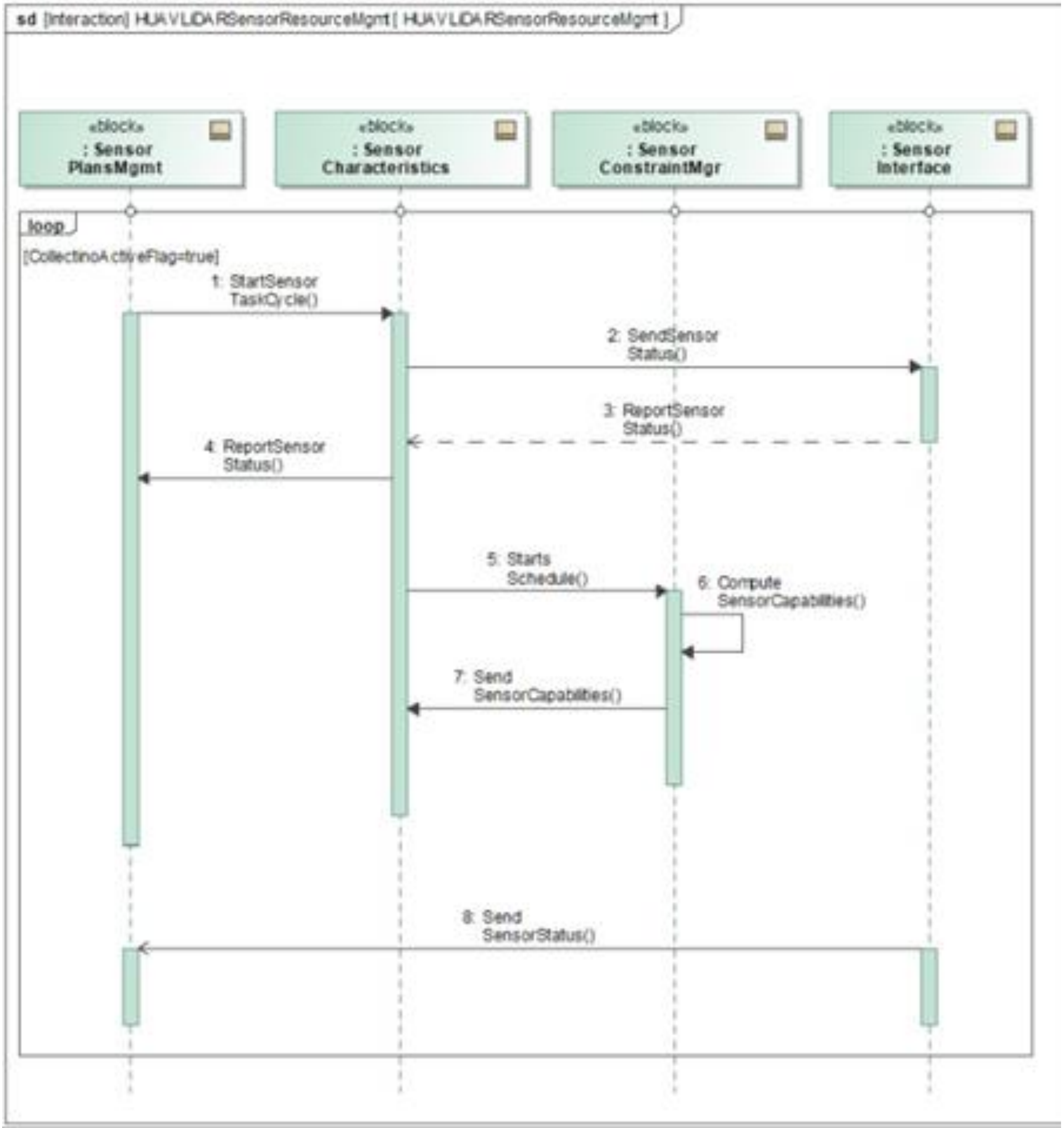

Figure 12:: LV Non Stateful Behavior – SD

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Use Cases

The H-UAV use case supports modeling of primary behaviors (autonomous launch, hoover, climb, loiter, etc.,) and supplies a graphic layout which summarizes some fundamental architectural aspects. See Figure 13 and 14**.** Further, an essential element of the UC is a scenario which captures the logical flow of the H-UAV behavior and typically contain a primary and secondary set of activities. For the H-UAV, the primary set of activities would be the mission launch followed by hoover climb then dash to the area of interest and finally flying a mission profile to complete the fire surveillance and communication. The UC scenario also contains fault activities which detail the behavior in the event of a fault. For example, if the H-UAV experienced hack attempts against its guidance systems, the behavior would be to shut down two-way communications and fly a predetermined route / profile back to the base station.

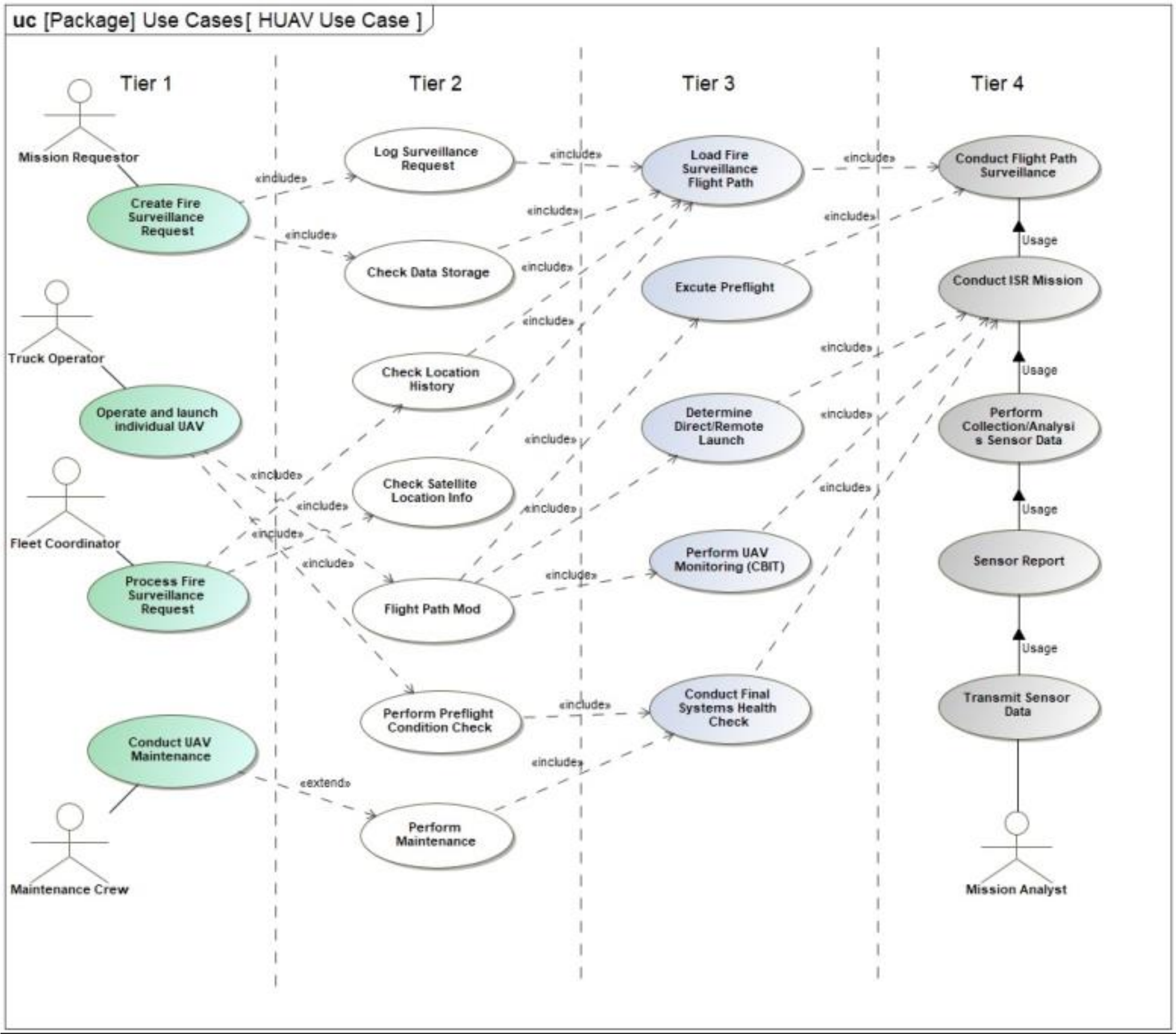

Figure 13: H-UAV Use Case Diagram

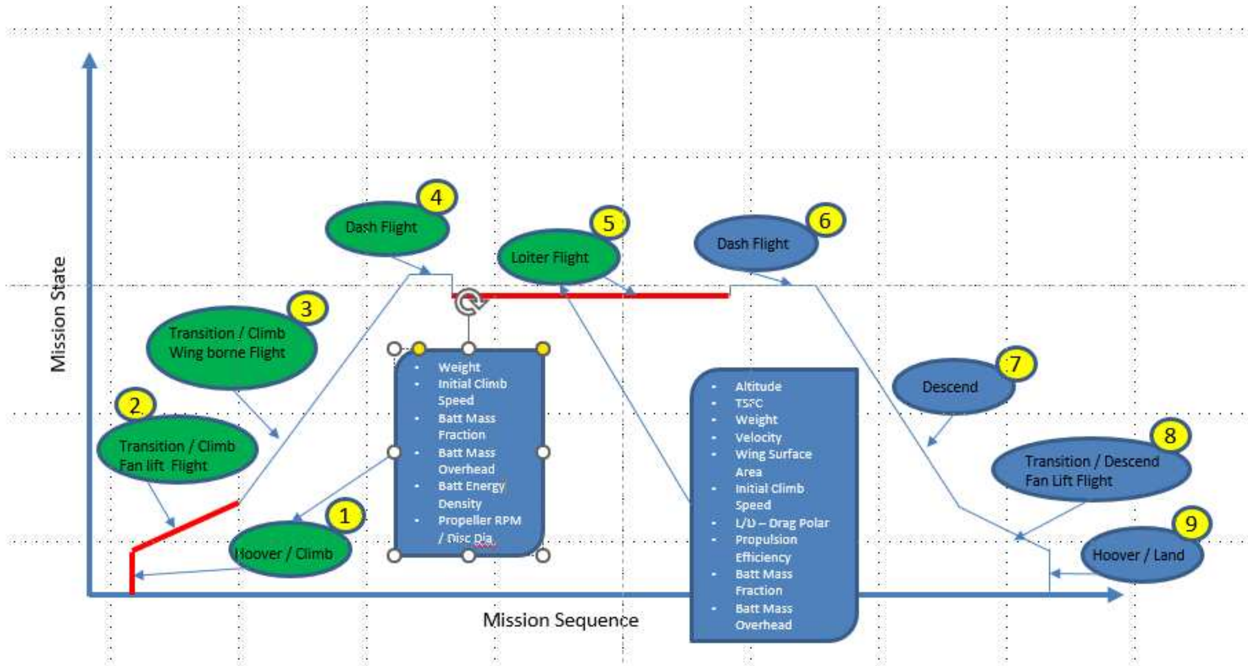

Figure 14: Typical H-UAV Mission Profile

Scenarios

Scenarios or a set of scenarios are needed in the specification of a Use Case, to explore the range of the H-UAV system behaviors within the UC. In most instances, there will be a primary scenario that describes what the system does under normal conditions, plus alternative Scenarios dealing with behavior under off nominal conditions. Reference Table 4

Table 4: H-UAV Operational Scenarios

Scenario S-1-17		
No.	**Section**	**Content/ Explanation**
1	Identifier	S-1-17
2	Name	UAV decreases mitigation response time
3	Author	Set Crawford
4	Version	V.1.1
5	Change history	N/A
6	Priority	Medium
7	Criticality	High
8	Source	Set Crawford
9	Responsible stakeholder	Cal Fire
10	Short description	FireCrow UAV detect Wild fire which was inadvertently started in area XX in less than XX time
11	Scenario type	desire state scenario
12	Goals	G-9-17 Reduce mitigation time for wild fire from XX to YY
13	Actors	UAV operator at mobile base station / operator monitoring UAV collected information / on board sensor systems / GPS systems / navigation systems
15	Precondition	wild fire started / UAV memory has location of recent wild fire in area XX / UAV has successfully completed pre flight / enroute / sensor checks
16	Postcondition	Cal Fire response crews are dispatch to location of wild fire for mitigation activities
17	Result	wild fire is mitigated before greater damage
18	Scenario Steps	1.UAV autonomously flies to area XX
		2. UAV flies predetermined surveillance pattern
		3. UAV access data base on locations of previous wild fires in area XX.
		4. UAV modifies surveillance pattern based on information from wild fire reports and information from LEO and GEO satellites so as to avoid areas of low concern
		5. UAV collect data / processes / sends data to base station.
		6. Cal fire determines appropriate response and dispatches mitigation crews
		wild fire is mitigated before greater damage
19	Qualities	Q-7-42: wild fire location and size communicated to Cal Fire in less than XX minutes.
20	Relationships to other use cases	S-2-17: UAV mission resilience
		S-3-17: UAV flexible landing capability
21	Supplementary information	The competing system GOES XX realizes a similar scenario

Activity Diagrams

Activity diagrams are the primary unit of behavior and are used to graphically depict the flow of a use case scenario or a process. As such, they are one of the most important artifacts of the MBSAP method and add structure to the various system behaviors. Reference Figure 11 and 12 where at a high level the fire detection and communication behavior are captured. A fire surveillance request is received by the base station and transfer to the UAV mission operations teams then to the H-UAV then to on board systems to launch and fly the UAV to the area of interest. Finally, in case of a wildfire detection, critical information is collected then transmitted back to the base station for communications to fire mitigation services. See Figures 15 and 16.

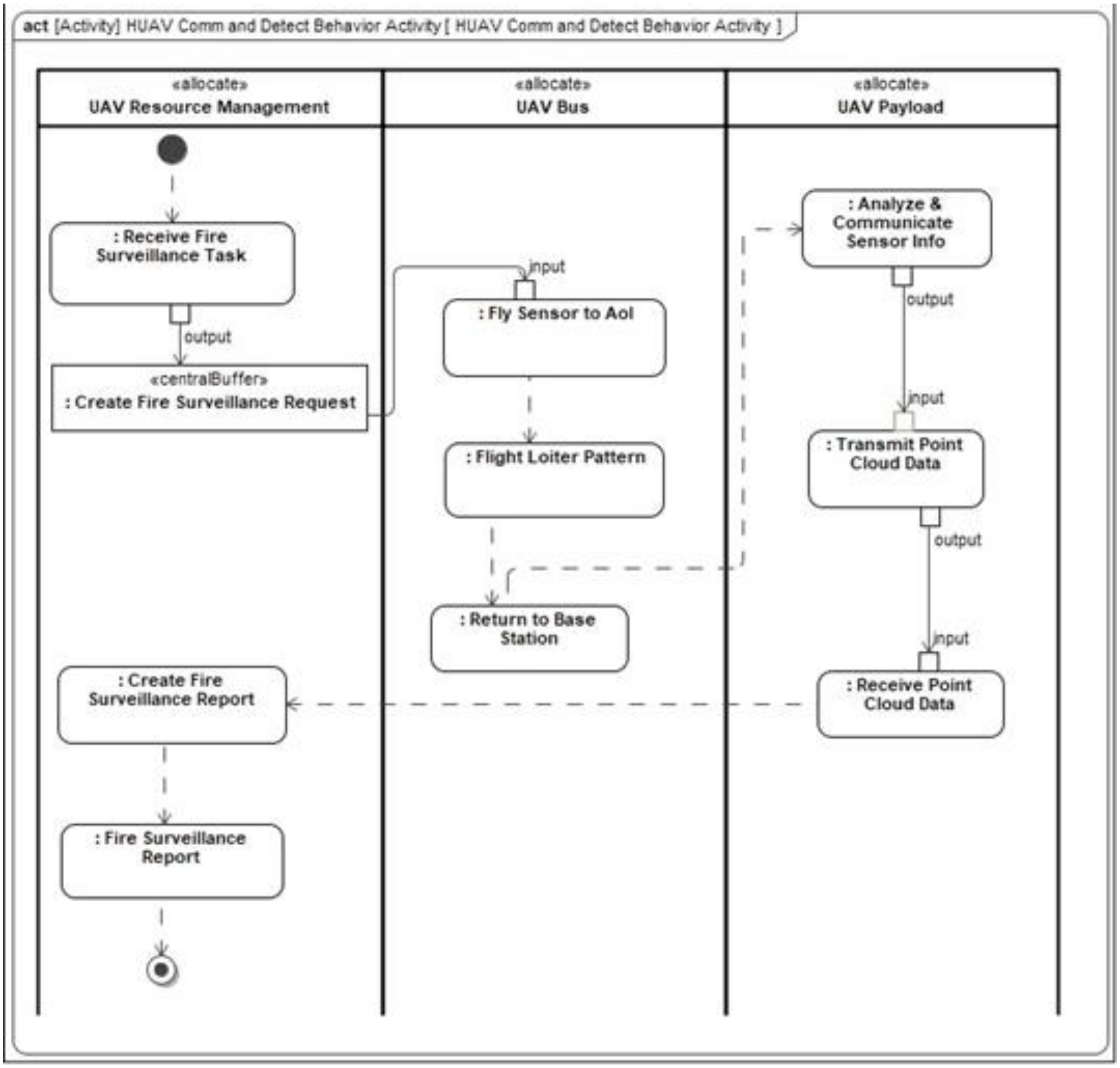

Figure 15: Fire Detection and Communication System Activity Diagram

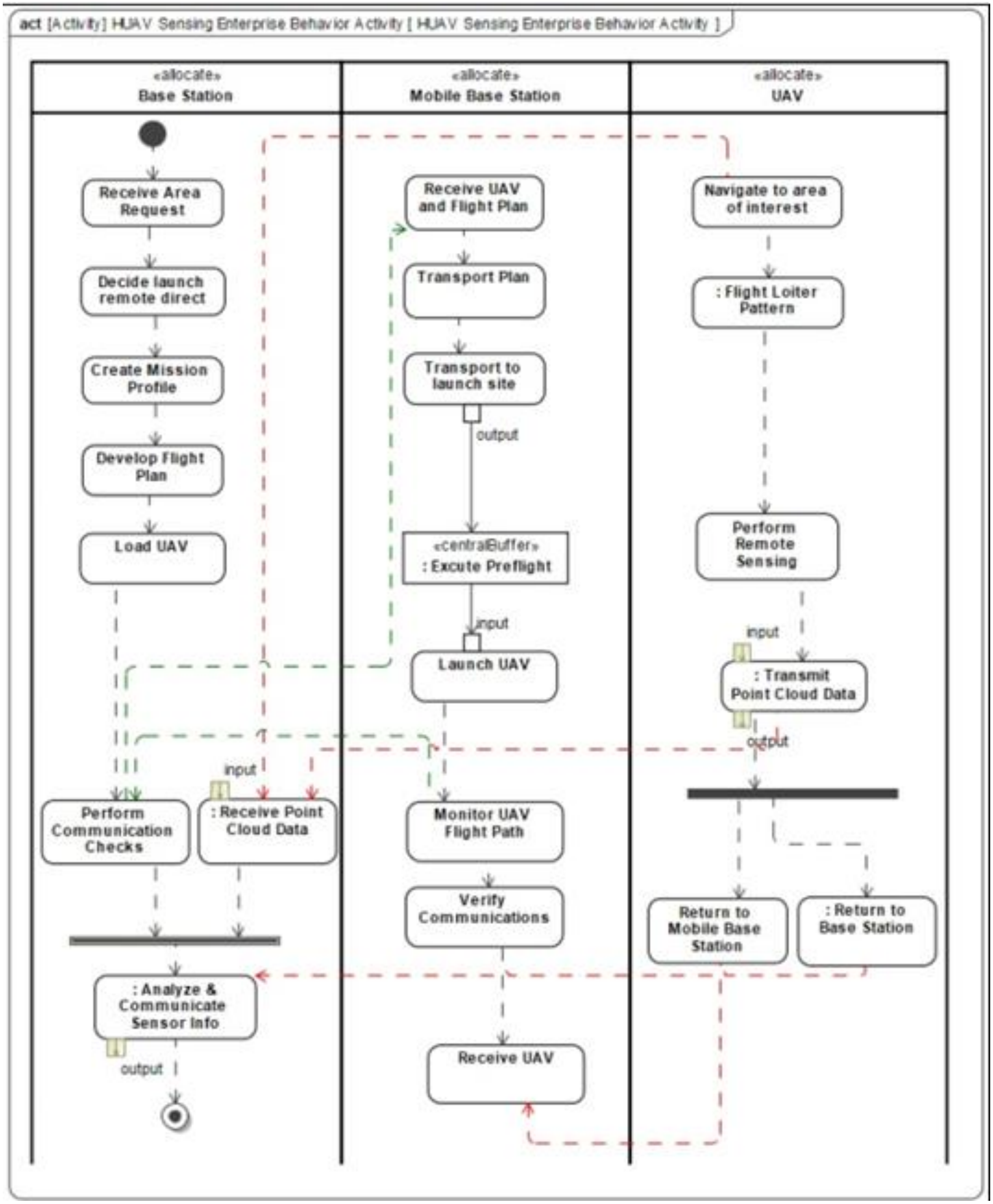

Figure 16: Enterprise Behaviors – Activity Diagram

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State Machine Diagram

The FD&C H-UAV enterprise State Machine Diagrams (SMDs) show stateful behaviors at the enterprise level and offer an immensely powerful and flexible means of modeling behaviors. Simulations are conducted using a combination of MATLAB, At Risk and Excel to model behaviors and explore sensitivities of critical design parameters for the H-UAV subsystem. See Figure 17

Some of the more salient features of the SMDs are.

- Modeling concurrent behaviors such as operations that execute simultaneously.
- Using nested CAs (embedded algorithms within super algorithms) to decompose complex behaviors.
- Accounting for actions that can be precisely associated with specific points in a behavior or computation.

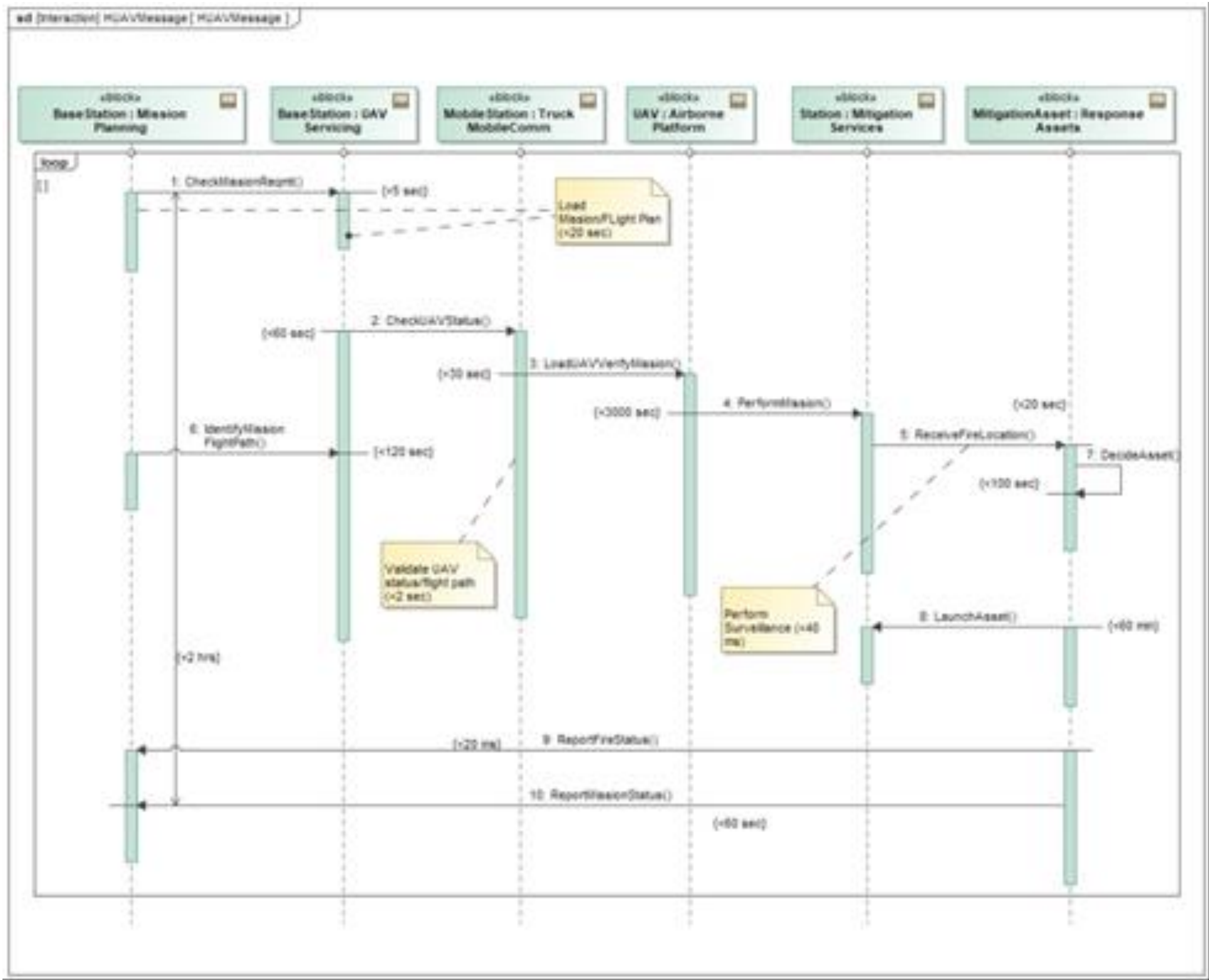

Figure 17: SMD - Enterprise Behavior

Contextual Perspective

In the preceding discussions, the focus has been on the use of formal modelling using SysML to build the fire detection and communications / H-UAV OV artifacts. Thus far, the emphasis has been on applying formal modeling, focused on SysML models, to build the OV. However, there are other important artifacts / documents which will inform the system architecture and other models like the executable model instantiated to evaluate behaviors against stakeholder requirements. These documents are captured in for lack of a better description, the contextual perspective. Reference Table 5

- http://www.barnardmicrosystems.com/UAV/uav_design/guidelines.html
- FAA Navigation Data Base
- FAA Regulations
- Texas A&M study on UAV cybersecurity - http://students.cse.tamu.edu/emy/report.pdf
- Thesis by Twanda Manangadze - Forest Fire Detection for near real time monitoring using geostationary satellites - see section 2.6.3 "Fire Detction Accuracy"
- research paper by Prof Brigitte Ledlon - "use of Remote Sensing in Wildfire Management" - web site www.intechopen.com/books/sustainable-development - see section 3.1 Fire Detection
- The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences. Vol XXXVII Part B1. Beijing 2008
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- Dr. Bradley, T.H., Rhoads, G., " Design Space Exploration for Electrically Powered Vertical Take-Off and Landing Unmanned Aerial Vehicles ", 9th Annual International Energy Conversion Engineering Conference, 31 July-03 August 2011, San Diego, CA
- Bradley, T.H., Moffitt, B., Fuller, T.F., Mavris, D.N., Parekh, D., " Hardware-in-the-Loop Testing of Fuel Cell Aircraft Powerplants", Journal of Propulsion and Power, Vol 25, No. 6, November-December 2009

Figure 18: OV Contextual Perspective

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H-UAV Enterprise goals describe the objectives that must be achieved by the system being instantiated. They capture whether the H-UAV system data or the system functions are sufficient for achieving the high-level objectives in the requirements engineering analysis. The introduction of goals into the systems engineering process, helps inform the completeness of requirements analysis.[90]

Table 5: Contextual Perspective

Standards Categories	Typical Standards
Information Processing:	**Goals - Commonality, Interoperability**
-User Interface	-Operating System User Interface Standards
-Data Management	-Data Base Management
-Data Interchange	-Data formats and Markup Langauge
-Graphics, imagery	-Graphics, Imagery
-Operating Systems	-Portable Operating Systems
-Distributed Computing	-Character sets
-Environmental Management	-Naming Events
Information Transfer:	**Goals - Interoperability Among Nodes and Systems**
-Host Systems	-IETF Internet Host ans Standards
-Graphics and Imergary	-Graphics, Imagery and Video Transmission Protocols
-File Transfer	-File Transfer Protocol (FTP)
-Remote Treminals	-Telecommunications Network (TELNET)
-Time Synchronization	-Network Time Protocols (NTP)
-Global Positioning System (GPS)	-GPS Standards
-Identification Friend or Foe (IFF)	-FAA and International IFF standards
-Network & Telecommunications Management	-Wired, Wireless and Optical Media Standards
Mission-Specific Standards	**Goals - Common testing and operations**
-Standardized testing	-MIL-STD-810F
-Aircraft Electric Loads Analysis	-MIl-E-7016
-Small Unmanned Aircraf Systems (Part 107)	-AC 107-2
-Public Aircraft Operations	-AC 00-1.1A
-Unmanned Aircraft Systems	-FAA Order JO 7200.23.
Human-Machine Interface (HMI):	**Goals - Uniformity and Interoperability for Users**
-User Interface Design	-Multiple Graphcal User Interface (GUI) Standards
-Style Guides	-X-Windows, Mission-Oriented Style Guides
-Symbology	-FAA guide UAV registration marking

Table 6: H-UAV Goals

number	Goal
G0	The system shall reduce wildfire detection time to less than 4 hrs
G1	The system shall Detect the location of a wild fire
G2	Communicate location of a wild fire
G3	Communicate location in a timely manner
G4	System must be affordable for agencies like Cal fire
G5	System must leverage existing technologies for remote sensing/ position/ guidance/ communications
G6	System must be able to be operated by a trained operator with minimal certifications
G7	System must provide uninterrupted surveillance of subject area
G8	System must be able to fly to and surveil the subject area autonomously
G9	System must have remote pilot capabilities
G10	The System shall be hack resilient

Coupled Architecture

In the OV early and less refined models are developed and are later refined in the subsequence Viewpoints as the system instantiation takes shape. These models, whether operational or process flow, can be invaluable tools with which, to conduct simulations and inform the consistency of early system behaviors with shake holder requirements. For a flow diagram of an executable model. Reference Figure 19 [15][20][21][22][27][79][90]

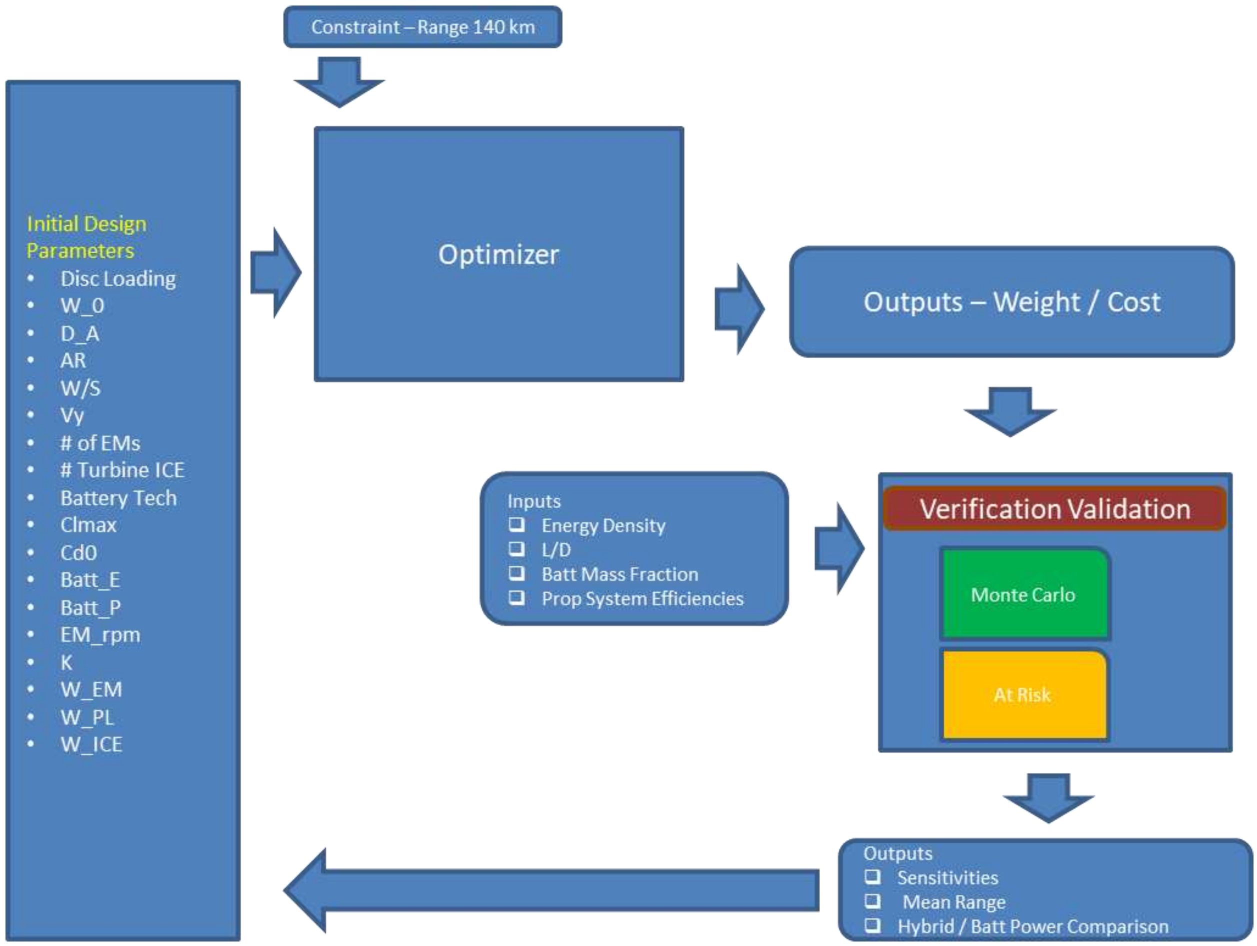


Figure 19: Executable Model

The H-UAV coupled architecture / executable model was developed and optimized using SysML along with a series of interlinked excel spread sheets (CAs) with interfaces to a MATLAB script and an @Risk program. The model accounts for the most critical high level operational behaviors of the fire detection and communication UAV [89][90]. See Table 7 for list of mathematical models (CA)s. The MATLAB script and the @Risk program were used to exercise the model during the simulation and verification / validation phases of the design exploration (DSE). Execution of the (CA)s expressed as

SysML parametric diagrams allows for the automatic updates of critical parameter value during simulations.

Table 7: List of Mathematical Models (CAs) [8][9][10]

CA Number	Nomentclature	Objective
1	Climb Power	Calculate power required to climb - thrust lift
2	Battery Sizing	Calculate weight of battery required
3	Range Loiter	Calculate UAV loiter range - hybrid
4	Range Loiter Battery	Calculate UAV Loiter range - Batt
5	Range Dash	Calculate Fuel required for dash phase of flight
6	Disc Loading	Calculate propeller disc loading
7	EM Data	Calculate function that relate power required to EM weight
8	ICE Data	Calculate function that relates thrust required to ICE weight
9	UAV Cost	Calculate UAV cost - function of payload weight and gross weight
10	UAV Payload	Calculate UAV payload weight range
11	Wing Loading	Calculate Stall speed / loiter velocity
12	Climb Thrust Fuel	Calculate ICE thrust and fuel required for phad]se of flight
13	UAV Weights	Calculate weights of UAV components
14	UAV Fuel Weight	Calculate mission fuel
15	Max Climb Rate	Calculate max climb rate
16	Max Climb Speed	Calculate forward velocity at max climb rate
17	Max Forward Speed	Calculate max forward speed
18	Max Climb at Ceiling	Calculate UAV service ceiling

Optimization Plan

There are a total of nine mission flight phases considered for exploration / optimization. The bounding two phases were initial climb and loiter range. The most important output of the Climb phase is the battery size and weight required. Loiter range is the other bounding phase because exploration and optimization would yield a UAV system fuel weight required to meet the required loiter range. The other 7 phases of flight are not optimized because results would not appreciably affect the UAV sizing method and design analyses. The results of the bounding phases are used to approximate the inputs needed to arrive at an optimal UAV configuration required to achieve mission requirements.[12][23][24][26][59][62][63][71][73]. See Figure 14

DSE Capability: Coupled Architecture

Our DSE method enables a Coupled Architecture since it is integrated with the MBSAP. This means that it is relatively easy to discover the impact of changing stakeholder needs to UAV architecture and vice versa.

For example, we can answer difficult questions like: Can we beat the optimum? Figure 20 shows that we can practically extend the range of the UAV by 100 km by scaling up (larger dimensions, weight, and larger fuel tanks etc.) and adjusting the vertical take-off speed. This will result in a larger area coverage per UAV. But now the individual wings and fuselage are heavier and larger so that the operator needs to be capable of carrying and assembling heavier parts. Furthermore, we may no longer be able to package 3 of the larger UAVs in the back of a mid-size truck so the means of land transportation to a remote location or the number of UAVs in the fleet will be impacted. Furthermore, the larger engines required may no longer be easily source-able requiring a purpose made gas turbine that will heavily impact the cost. Are these impacts acceptable? Well, it depends on the stakeholders' needs, operational scenarios and mission.

Another normally difficult question: What if in practice we find that the weight of the Sensor package (containing sensors: LIDAR, IR, Video Camera and pointing mechanism) is 7 kg and therefore larger than the allocated 6 kg. Can we still achieve the same range for the mission? A simple answer might be to save 1 kg elsewhere such as the Airframe, Propulsion and Flight Controls. However, Figure 20 shows that we have at least 3 high leverage directions to compensate for this: larger size, faster vertical take-off velocity and higher L/D through aerodynamic optimization.

Early is the MBSAP, process and operation models are developed and further refined as the architect synthesizes the system in various views.[89][90][104] These become valuable when integrated with trade-studies, DSE, digital twins, and simulations. We call this a coupled architecture/ executable model because it ensures that the systems structure and behavior stay aligned with or consistent with stakeholders needs, requirements and use cases, when something changes.

As the system develops, there is often the need to evaluate different bounding criteria and answer what if scenarios such as the two example situations cited above. Here the coupled architecture can give the answer quickly if the toolchain is seamlessly integrated. For example, we can change the mission/payload and bounding technology assumptions and recreate all the tornado charts containing actionable information about the optimal design and its sensitivity automatically.

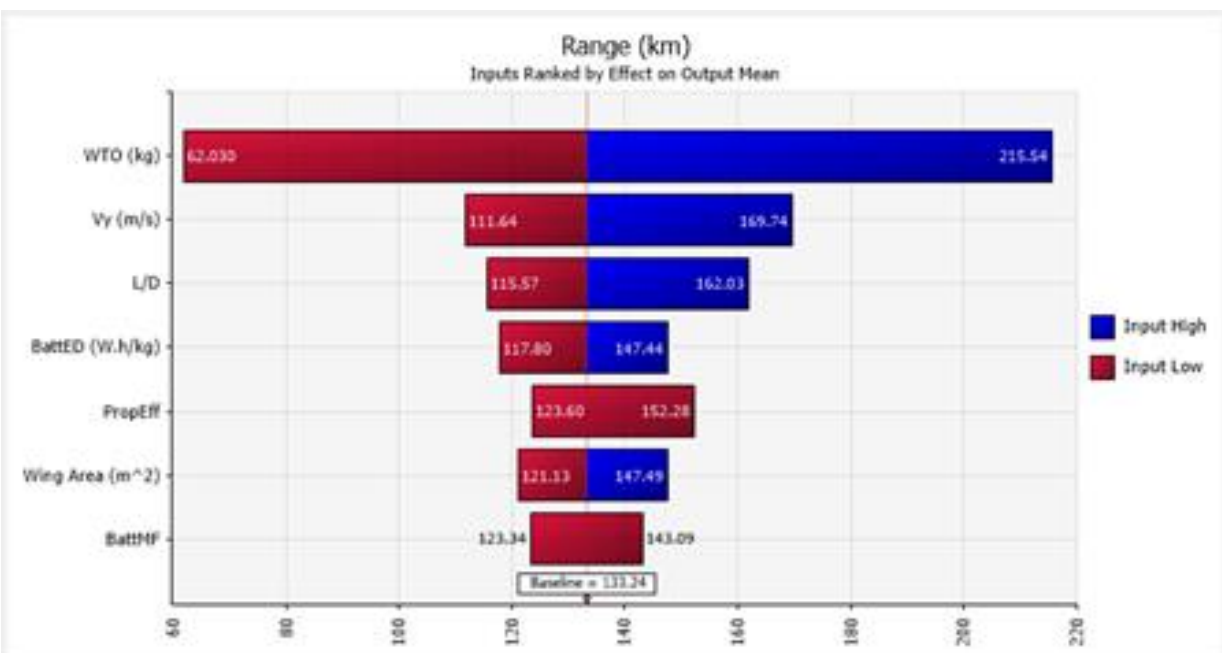


Figure 20: Tornado chart ranking the biggest design drivers for range of H-UAV

Modelling

Modelling is the process of creating a digital or soft representation of a physical entity or whole system. Models and especially, executable, or dynamic models, can be used to help the analyst or researcher understand system behaviors as a function of input parameter changes. To maximize the efficacy of a model and mitigate some of negatives associated with reliance of domain knowledge, models should be validated using real systems data or other validation strategies, to the extent possible. [41][42][62][63]. See Figures 20 and 21

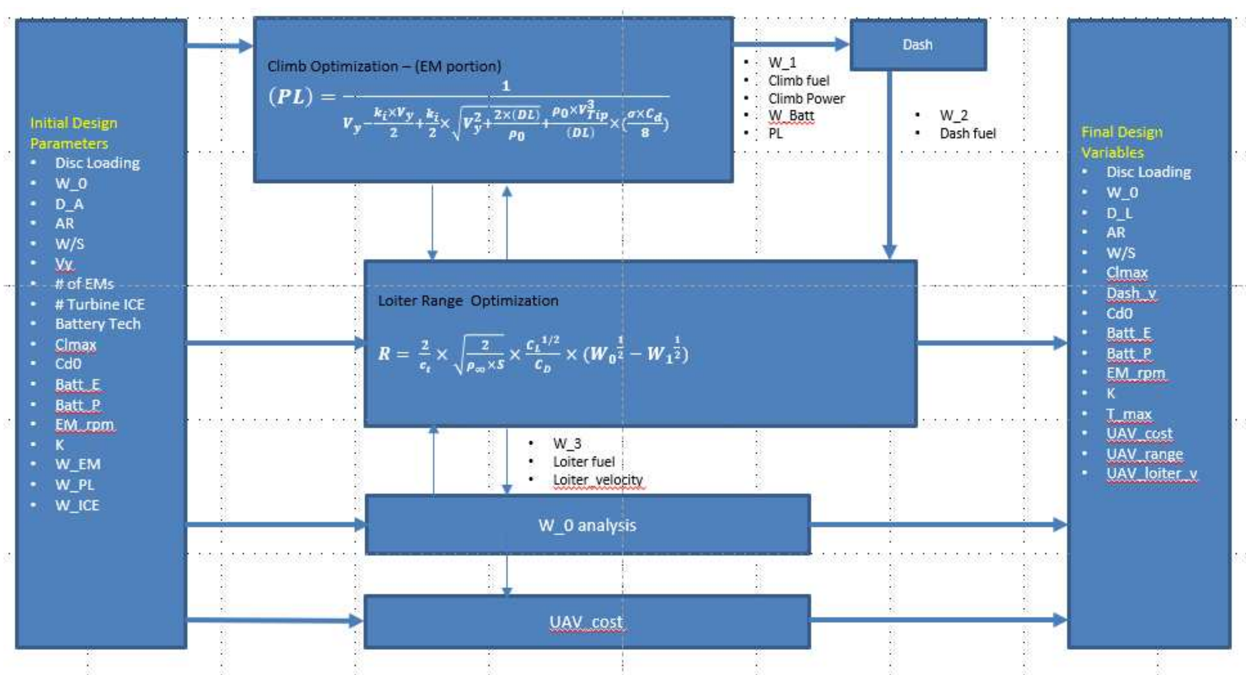


Figure 21: Executable Model – Optimization

Simulation

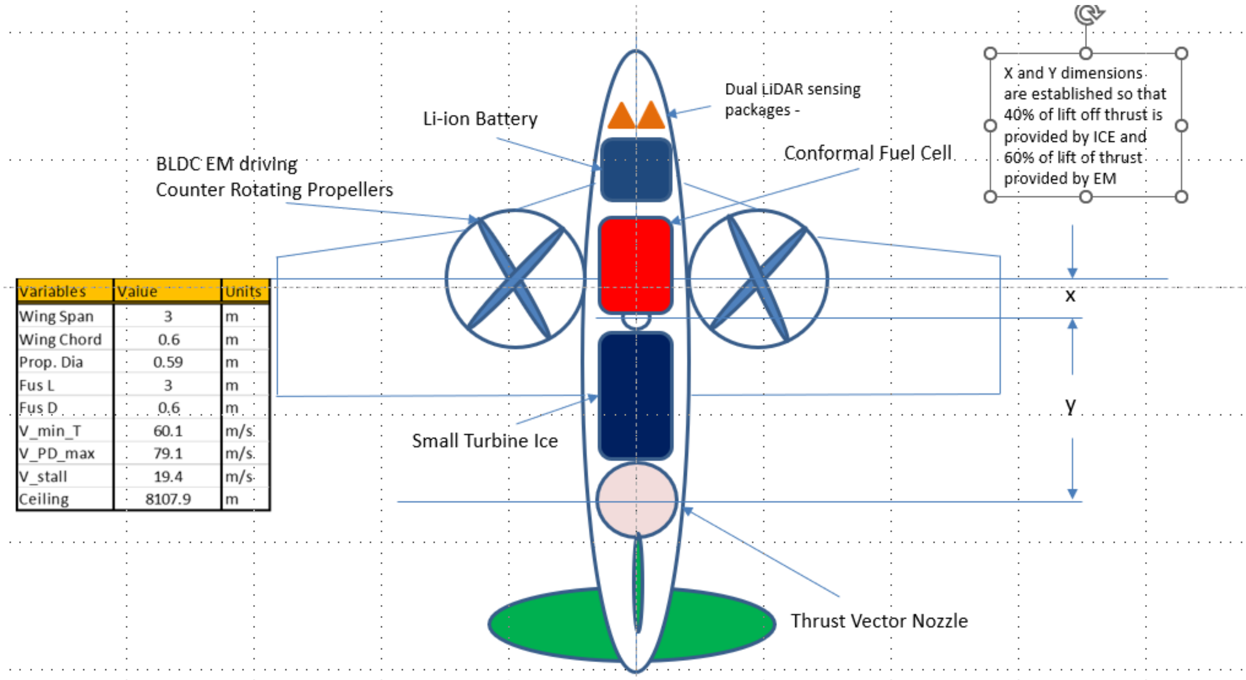
Simulation is the process of exercising a dynamic model in terms of time and/or space, which informs incremental validation of the system behaviors as the system design spirals through each phase of development.

There are several advantages in systems development when using model and simulation analysis. Simulations can be used as a cost-effective way of studying the effects of scenario changes on complex systems without affecting the real system or before changes are made to the real system. Models are easier than the actual physical system to upgrade and revalidate.[43] [57][58]

Design Perspective – Visualization

The LV includes a Model that defines the architectural content in the form of a block layout capturing system functionality content of the H-UAV node of the FD&C enterprise. [64][65][68][69][74][114]

In the PV, this is extended with one or more physical schemas that add physical metadata. See Figures 22,23, 24, 25, 26 and 27 for the landing/takeoff and loiter stages of the H-UAV as well as an output of a simulation run showing relative specific cost comparisons.



Variables	Value	Units
Wing Span	3	m
Wing Chord	0.6	m
Prop. Dia	0.59	m
Fus L	3	m
Fus D	0.6	m
V_min_T	60.1	m/s
V_PD_max	79.1	m/s
V_stall	19.4	m/s
Ceiling	8107.9	m

Figure 22: Initial H-UAV System Layout

3rd concept

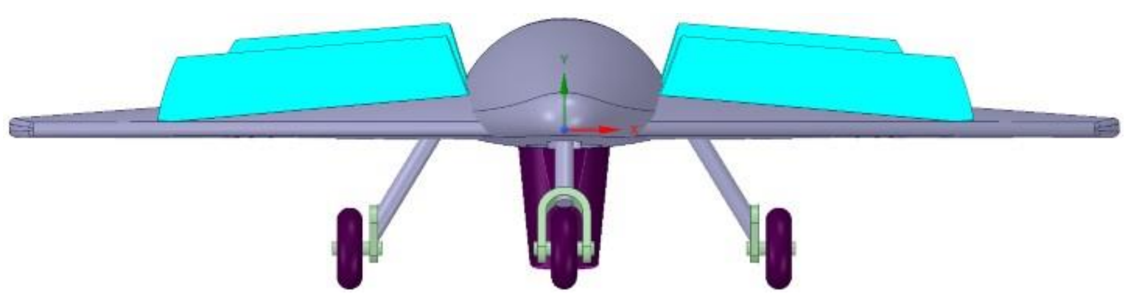


Figure 23: H-UAV Landing Configuration

3rd concept

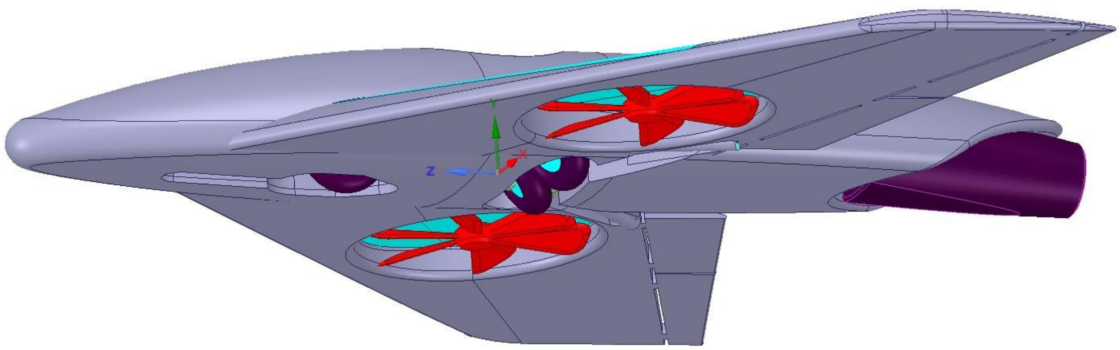


Figure 24 : H-UAV Loiter Configuration

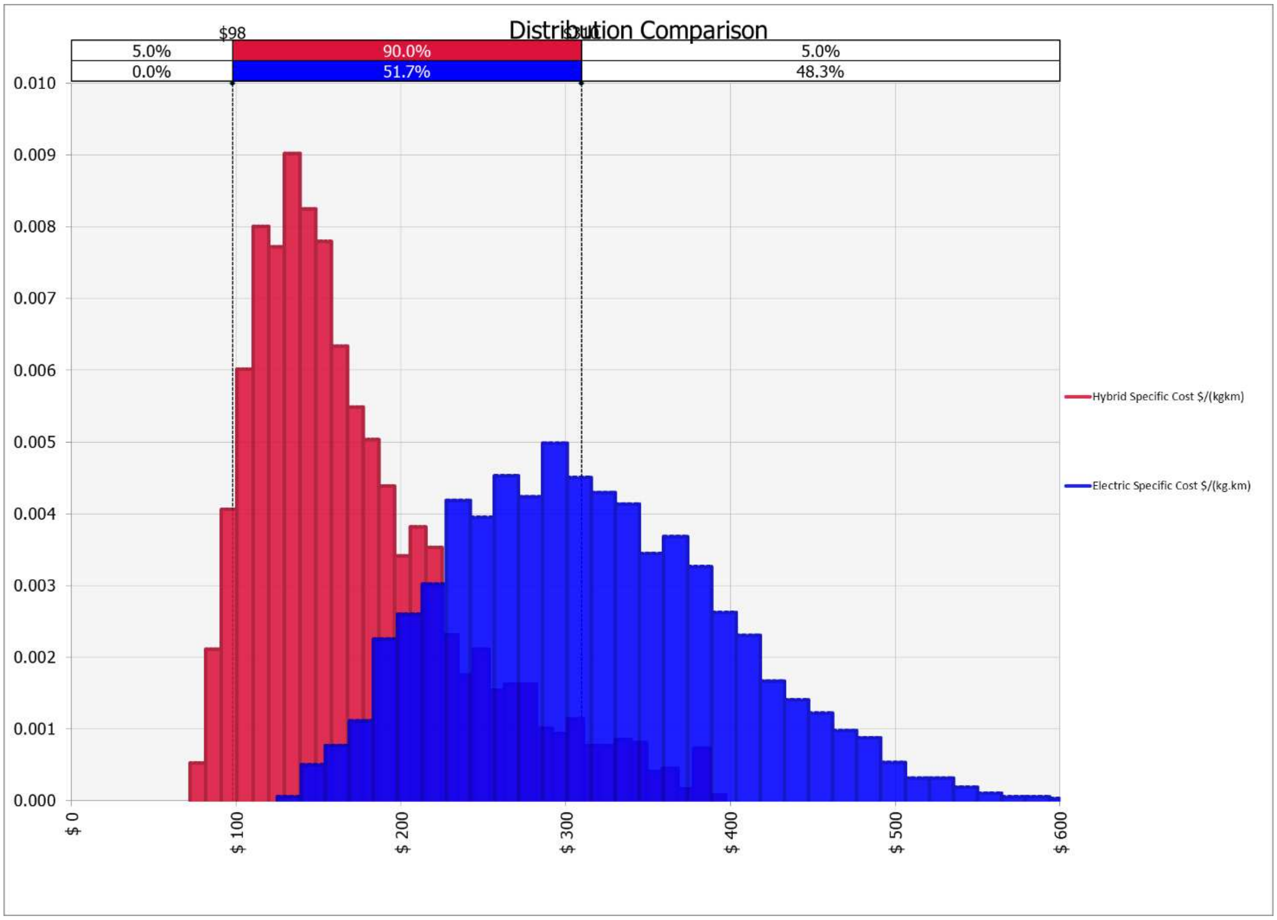


Figure 25: H-UAV Specific Cost Comparison

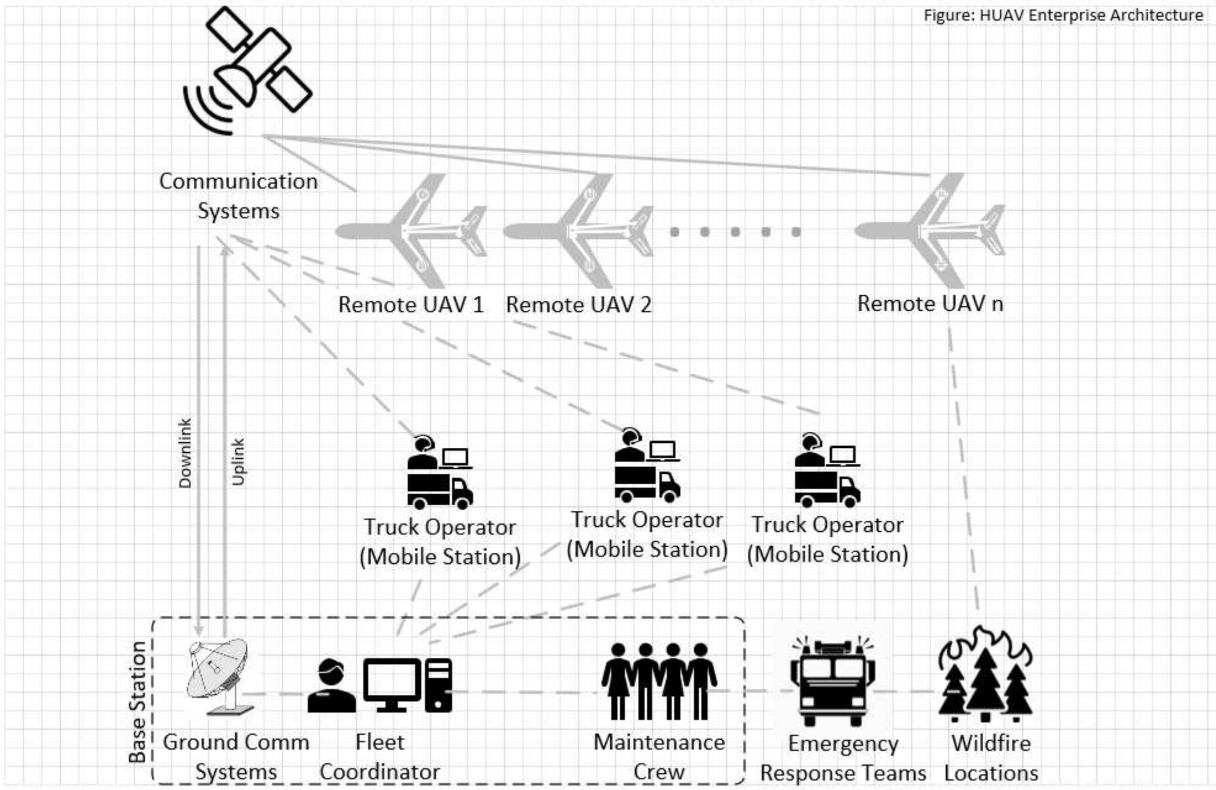


Figure 26: H-UAV Enterprise Architecture

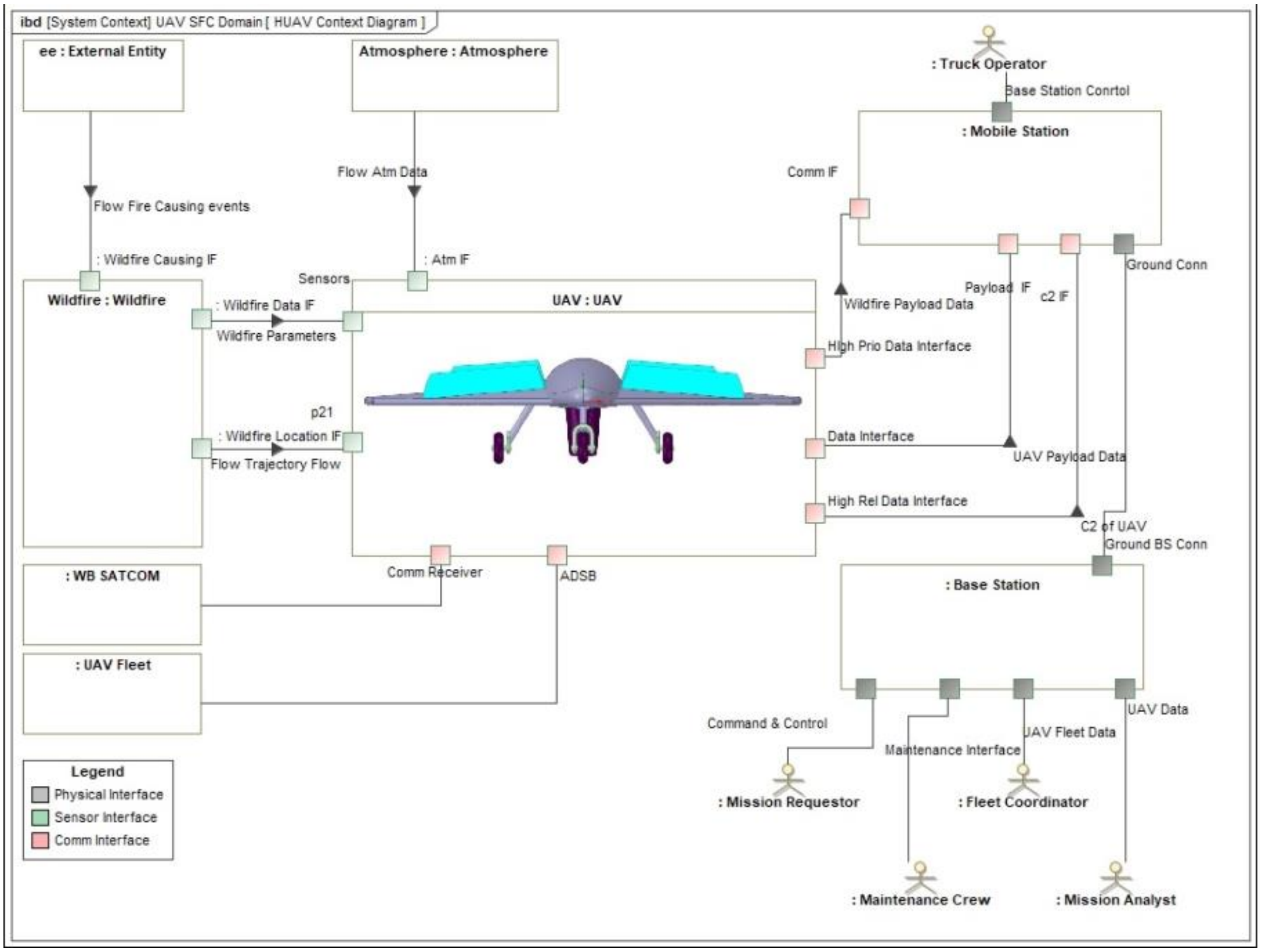


Figure 27: H-UAV Context Diagram

Cybersecurity

Cyber security can be defined as “Prevention of damage to, protection of, and restoration of computers, electronic communications systems, electronic communications services, wire communication, and electronic communication, including information contained therein, to ensure its availability, integrity, authentication, confidentiality, and nonrepudiation”.

The overall strategy for the FD&C H-UAV enterprise is a multilevel approach starting with robust systems design architecture, rigorous training program for both the operators as well as trusted personnel who would be granted access to the system data base, and finally assignment rotation to avoid some to the pit falls of insider attacks.

System architecture would include a combination of DiD / Next Generation Layered Defense – Zero trust processes where an attacker would have to penetrate multiple layers of safeguards to reach sensitive resources. Further all operators would be required to utilize strong access control particularly in the field at remote location where the UAV will be deployed to surveil areas of interest. An example here would be a secure token given to the operator and is synchronized with another token at a secure site. The operator would be required to enter the random number generated by the token along with a strong password and user ID, subject to change at some frequency. All traffic would be inspected and analyzed / logged to detect malicious traffic. If the H-UAV system were to detect continuous malicious traffic, the system software would command entrance into a safe mode where the H-UAV would fly a pre- programmed flight pattern or return to base.

The enterprise approach starts with a solid cyber security policy endorsed at the highest level of management and later flow down to system engineering and security operations functional groups.

It is important that the system incorporates cyber security measures around command-and-control communication to ensure that, the operators maintain reliable and continuous control of the H-UAV for obvious reasons.

In addition to the obvious damage to intelligence and loss of very expensive equipment, there can be the added loss of enabling technological advancement to an adversary.

Vulnerabilities were identified with insider threat ranking amongst the highest. There are many practices which can be implemented to identify and counter insider threats. One such method is to practice job rotation but prevent the accumulation of privileges to minimize the accumulation of data access.

Top level security requirements were identified, and associated risks analyzed. The risk of the H-UAV system being hacked / hijacked was treated by increasing the operating system software security.

Possible applications for cryptography are Secrecy or Confidentially – This approach converts plain texts into unreadable cipher text using different classes of cipher - Block cipher or Stream ciphers. Block cipher acts on a single block (often 64 bits) of plain texts / combines substitution functions for “confusion” and transposition functions for “diffusion”; avalanche effects – small changes in input to algorithm cause large differences in the output / commonly uses successive layers of “substitution boxes” (S-boxes”) defined by lookup tables and controlled by key Stream cipher acts on continuous data stream, one bit at a time. This method is faster than block cipher but overall, less secure, and less used because of the difficulty of creating truly random keystreams.

For the H-UAV application – data collected and processed would be encrypted as part of a layered security approach so that if an adversary were to access the data – it would be of little use.

Network security would be implemented using; Simple Network Management Protocol (SNMP) – using a manager on a server that maintains a management information data base (MIB) and “agent” installed on monitored devices.

- Vulnerabilities include exposing invaluable information about network configuration services, spare names, spare paths, etc., to the attacker.
- Counter measures are that managers must have exceptionally strong frequently changed passwords / must replace vendor default passwords / should assign unique passwords to every network segment / must close ports 161 / 162 to untrusted networks, especially the internet/ use encryption, authentication, and message integrity.

The H-UAV sensor information processing in the second enclave on board the H-UAV and likewise would be protected its UTM and End point security – intrusion Detection / Prevention System (IDS / IPS).

Access to processed information would be further control using virtualization – the use of a software abstraction layer to cause underlying information resources to look like something else. Virtualization improves security, especially in the cloud environment in several ways – Isolation of virtual networks and environments from each other and from the physical platforms.

Physical security is an essential part of a complete, resilient, balanced, affordable and operationally effective cybersecurity solution. Essential tenants are Included in the requirements baseline, part of risk analysis and treatment and is complementary to other elements of the security posture. Physical security requires ongoing assessment and updating like all other security controls.

Summary

Implementing the MBSAP structured approach to the wildfire detection and communications systems engineering research, and in particular, the service orientation, enabled the appropriate trade analyses and collection of comprehensive functional and non-functional requirements, those requirements were mapped to behaviors which led to services and formed the basis for the development of goals and scenarios, which in turn captured critical enterprise and subsystem behaviors. These behaviors were validated by simulations using a coupled architecture executable model. The results of multiple simulations during the Design Space Exploration (DSE) phase of the research, further substantiate, the initial finding of the trade study. The H-UAV is an affordable d platform which meets stakeholder requirements for a locally owned and operated fire detection and communication system. Furthermore, this chapter shows that the MBSAP method is systems/application agnostic: i.e., equally applicable to systems that have significant software, electronic and mechanical hardware content: i.e., not just applicable software for which it was originally developed.

Chapter 3

High Level Trade Study

Summary

There are several factors affecting wildfires: detection, speed of communication/response time, resources/politics/climate change/infrastructure to fight fires, and prevention education. Since a wildfire double in size and intensity every 3 to 5 minutes and response times tend to be 10 to 15 minutes at best, detection and response are the most critical factors, and as such, researchers will concentrate in these areas. It would be irresponsible not to note here that humans are seven times more likely to cause a wildland fire than a natural cause such as lightning, so perhaps education and prevention would be the most cost-effective method for wildland fire mitigation. We detect wildfires much like we did 200 years ago, relying primarily on spotters in fire towers or on the ground or on reports from the public. We then augment this information by aerial reconnaissance and lighting detectors that steer firefighters to the ground strikes, which are one of the more common wildfire sparks.

Satellite and other aerospace technology, remote sensing, and computing have advanced to the stage where it is now possible for orbiting geostationary or polar orbit satellites to reliably distinguish small but spreading wildfires with few false alarms. We could build and launch a satellite for a few hundred million dollars—a fraction of the nation’s USD 2.5 billion budget for firefighting. A private state or federal entity could fund such a satellite. In addition, we intend to explore in this paper other aerospace platforms which engineers can develop and deploy to mitigate the damage wildfires cause. Wildfire damage and suppression operations costs are growing exponentially. California has spent a reported USD 700 million in fiscal year 2017 on wildfire suppression operations. This was more than USD 300 million above the budget amount and surpasses the previous report set in 2015. See Figure 28 for the projected growth of the 10-year average cost of fire suppression (in 1000 USD) through 2015.[107][111]

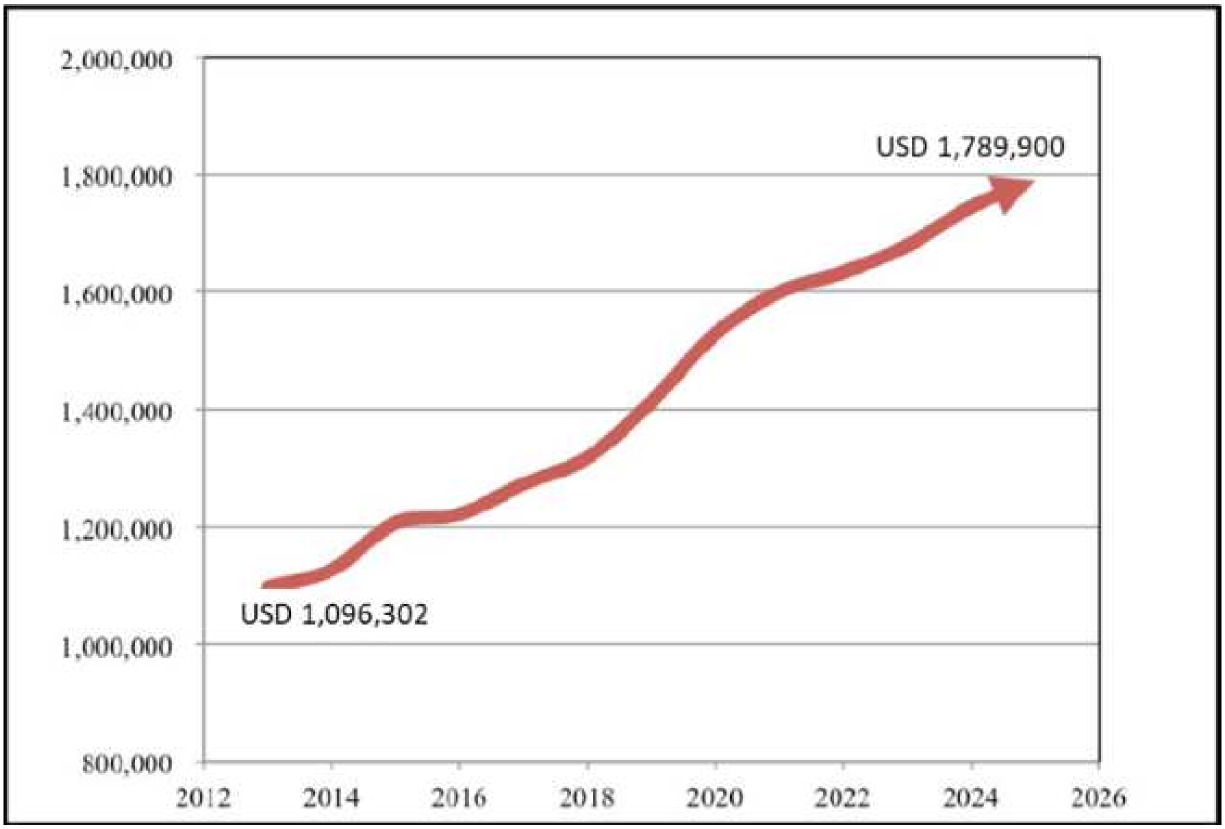


Figure 28*: Project growth of the 10-year average cost of fire suppression (in 1000 USD) through 2015 (https://www.fs.fed.us/sites/default/files/2015-Rising-Cost-Wildfire-Operations.pdf)*

Modern system engineering techniques will anchor the trade study to ensure that we arrive at the best solution which meets the key requirements in a clear and methodological fashion with minimal subjectivity. The trade study will include:

- a requirements analysis phase where we will develop and use goals and scenarios to arrive at a final set of top-level requirements.
- a concept exploration phase, where we will consider an appropriate number of alternative solutions with an adequate amount of technology diversity.
- a concept definition phase, where we will conduct first level comparisons of the merits of the alternative solutions.
- a concept validation phase, where we will examine sensitivities of MOEs.
- an integration and evaluation phase, where we will examine test concepts.
- a post-development phase, where we will consider design for production and transition from design to production.
- an operations and support phase, wherein we will examine service support and possible modernization.

We initiated the trade study with a needs analysis that included an assessment of predecessor systems, a review of relevant publications, and an interview with subject matter experts. The output of the needs analysis was a set of objective statements used to brainstorm a set of concepts to satisfy the new system needs.

Concept exploration includes a review of eight concept options with appreciable technology diversity for a reasonable balance and risk tolerance. The platform options considered are:

- Geosynchronous orbiting satellite system (geostationary (GEO)).
- Polar orbiting satellite system (low earth orbit (LEO)).
- Hosted payload.
- Unmanned aerial vehicle (UAV).

- Rotorcraft.
- Fixed wing.
- Hybrid airship.
- Data retrieval and management system.

Early research results show that the leading concept for fire detection and communication is the UAV transitional concept. A transitional hybrid propulsion UAV configuration that we could outfit with a remote sensing payload compliment based on steerable light detection and ranging (LiDAR) technology with associated functional equipment such as global positioning systems (GPS) and inertial measurement units IMU is the leading concept.

The overall strategy for the trade analysis is to break the study into six separate subsystems starting with a high-level trade, followed by a simulation/validation exercise, a re-examination of the system architecture, testing, risk analysis, and a brief discussion/possible application of cybersecurity onto the leading platform solution. We will distill necessary details for each subsection, with continuous validation of measures of effectiveness for the leading solution. The trade study will conclude with a final re-confirmation of the merits of the leading solution against an aggregate or alternative solution.[92]

High Level Trade

The objective is to complete an initial trade study of a technologically diverse set of concepts and converge on a system solution to move into the next phase of development and proof.

Simulation/Validation

The objective of the simulation/validation is to determine the basic parameters for the leading system solution given a coverage area and detection time target. Some of the basic answers required concern the fuel capacity needed for a typical mission. Given the fuel capacity, what is the total mass of the system and does that total mass still fall within the original system guidelines?

Model-Based Systems Engineering (MBSE)

The over-arching objective is to utilize an MBSE approach to drive the necessary systems engineering rigor into the development of design details for the leading concept. The goal is to develop a set of analytical, system architectural, and validation models for the UAV rotorcraft to complete a more detailed requirements analysis with goals and scenarios to arrive at a composite set of actionable requirements. We will reexamine the benefits of a rotor-wing versus fixed-wing UAV configuration.[106]

Testing/Verifications

The objective of testing and validation is to complete several levels of components and systems testing by using a surrogate platform to evaluate the capability of the LiDAR sensor to detect a simulated wildfire. After completion of this subsection, certain aspects of the concept of operations should be validated. For example, one of the major design differentiators is the use of a gimballed sensor to increase off-nadir detection. We postulate that gimballing the sensor could increase the footprint for a single pass, and thus decrease the number of surveillances passes required, and by extension, decreasing the time required to detect and communicate the location of a wildfire.

Risk Analysis

The objective for the risk analysis review is to utilize proactive risk management based on the standard risk model and utilize tools discussed in the text, *Proactive Risk Management* (Smith and Merritt 2002), to examine risks that might be associated with the development and deployment of the leading concept and present several examples of mitigation strategies.

Cybersecurity

It is important that the systems incorporate cybersecurity measures around command-and-control communication to ensure that the operators maintain reliable and continuous control of the UAV for obvious reasons. In addition to the obvious damage to intelligence and loss of very expensive equipment, there can be the added loss of enabling technological advancement of an adversary. The objective of this section is to explore the vulnerabilities and present possible mitigation architecture for the UAV system solution.

Consider Alternative Solutions

The objective of this section is to reaffirm the merits of the leading solution. There may be other alternative solutions (aggregate solutions). An example is an aggregate solution where we can exploit information from both LEO and GEO satellites already in operation to target and minimize the area that a UAV would have to surveil for wildfire detection and mitigation. Along with the incorporation of wildfire propagation history and topography, we may further reduce the coverage area leading to an improvement in detection and communication time.

Needs Analysis: Objective Statement

The needs analysis was initially completed and included an assessment of predecessor systems, a review of relevant publications, and an interview with subject matter experts. The need was determined to be technology- and needs-driven. The output of the needs analysis was a set of objective statements used to brainstorm a set of concepts to satisfy the new system needs:

- Develop a system that will detect and communicate the location of a wildfire before the fire has had chance to grow in intensity.
- The system must be relatively inexpensive to operate for state-run agencies like Cal Fire and others.

- The system must leverage existing technologies for remote sensing/position/guidance/communications.
- The system must be able to be operated by a trained operator with minimal certifications.
- The system must provide uninterrupted surveillance of the subject area at times of peak concern.
- The system must be fully autonomous with limited remote pilot capabilities.

Legacy Systems Fire Detection Methodologies

Fire detection is accomplished by comparing wavelengths of thermal bands located in the middle of the infrared and thermal parts of the spectrum. Different satellite sensors detect hot spot pixel wavelengths in these bands to determine the location, size, and intensity of a possible fire.

There are several different sensors used for fire detection:

(1) The MeteoSat Second Generation Spinning Enhanced Visible and Infrared Imager (MSG SEVIRI).

(2) Moderate Resolution Imaging Spectroradiometer (MODIS).

(3) National Oceanic and Atmospheric Administration (NOAA) Advanced Very High-Resolution Radiometer (AVHRR).

MSG SEVIRI observes the earth with improved accuracy and provides data in 12 different wavelengths within the visible and infrared spectrum. Some of the wavelengths are 0.6 nm, 3.9 nm, 8.7 nm, 9.7 nm, 12.0 nm, and 13.4 nm. Since different bands respond differently to hotspots, we must determine which band is best for the sensor in question to use for fire detection. Based on literature, 3.9 nm is the best band to use for this sensor.

MODIS sensor channels are used for fire detection bands located at wavelengths from 3.66 to 14.385 microns. From literature, wavelengths between 3.9 and 4 microns are best for fire detection with this sensor type.

AVHRR is a very high-resolution sensor used to detect surface temperature. See Table 1. The term surface covers a variety of surfaces including clouds, sea, or other bodies of water. The sensor was first used on the TIROS-N spacecraft (launched October 1978).

Table 8: NOAA AVHRR (http//noaasis.noaa.gov/NOAASIS/ml/avhrr.html)

AVHRR/3 Channel chatacteristics			
Channel number	Resolution at nadir	Wavelength (um)	Typical use
1	1.09 km	0.58 - 0.68	Daytime cloud and surface mapping
2	1.09 km	0.725 - 1.00	Land-water boundaries
3A	1.09 km	1.58 - 1.64	Snow and ice detection
3B	1.09 km	3.55 - 3.93	Night cloud mapping, sea surface temperaature
4	1.09 km	10.30 - 11.30	Night cloud mapping, sea surface temperature
5	1.09 km	11.50 - 12.50	Sea surface temperature

The most suitable bands for fire detection, given the three sensor types and from a review of literature, are 3.9 to 4.0 nm for MODIS and 3.7 nm for AVHRR [103]. However, we cannot use these bands alone; we must compare them with the least responsive bands—the longest ones—from 13.4 nm to 13.9 nm.

Of the three legacy sensor types, MSG is the most suitable for fire detection since it has better temporal resolution than MODIS and AVHRR. MSG is also not affected by performance degradation resulting from off nadir scan angles and solar angles. It has a higher saturation temperature than AVHRR and is about equal to MODIS. From literature, MSG has flagged the highest percentage of fires with 88% with the lowest omission rate of 12%.[103]

Proposed Fire Detection Methodologies: LiDAR

LiDAR is a remote sensing technology that measures distance by illuminating a target with laser light and analyzing the reflected light to build a bitmap of the target area. Several different wavelengths are in use today; however, the discussion will focus on the longer wavelengths (eye safe), 1,550 nm. The human eye cannot focus on this wavelength which has the added benefit of not being visible by night vision goggles.

The premise of this study is that the analysis of the bitmap data, created by a UAV mounted LiDAR sensor, could be used to determine whether a fire exists, and its size and intensity. In addition, the analysis/reduction can be accomplished more quickly and with a greater degree of accuracy than the legacy system based on infrared technologies. Another advantage over other UAV systems is in mission planning to reduce detection time. We can reduce the surveillance area by integrating area topography, satellite data, and historical data into the algorithm used to calculate the actual area over which the UAV will fly a surveillance pattern. We theorize that, using the proposed UAV LiDAR systems integration approach, we can realize as much as 30%-50% reduction in the area, with a corresponding reduction in detection and communication time.[108]

Advantages of Geostationary Versus Polar Orbiting Satellites Versus UAV Systems

Polar orbiting satellites have a higher spatial resolution than geostationary satellites; however, there are problems with continuous data. We can mitigate this by using steerable sensors for off-nadir sensing as well as increasing the number of assets orbiting the earth. Geostationary satellites like MSG SEVIRI offer more persistent coverage over specific areas of interest and can provide images every 15 minutes. UAV systems can be very flexible and may have relatively lower costs to develop, deploy, and operate. Perhaps a combination of polar and geostationary satellite data utilized by a UAV operator for fine-tuned area coverage is the best approach for detecting dynamic phenomenon like wildfires.

Basic concepts to meet the stated system needs of the new system include the following list. Brainstorming and the Delphi technique were used to yield these concepts. Realizing the importance of technology diversity as well as a balanced risk tolerance approach, an expert knowledge review was used to make an initial assessment of the concepts presented:

- Geosynchronous orbiting satellite system (GEO).
- Polar orbiting satellite system (LEO).
- Hosted payload.
- Unmanned aerial vehicle (UAV).
- Rotorcraft.
- Fixed wing aircraft.
- Hybrid airship.
- Data retrieval and management system.

Concepts
Geosynchronous Orbiting Satellite System (GEO) Option

This option is a satellite platform placed in a geosynchronous orbit (sometimes abbreviated (GSO) over an area of interest. This orbit around the Earth would be equatorial with a western longitudinal slot to cover areas of the United States. California, Florida, and Wyoming are areas particularly susceptible to wildfires. We would use the orbital period of one sidereal day, intentionally matching the Earth's sidereal rotation period (approximately 23 hours, 56minutes, and 4 seconds). The synchronization of rotation and orbital period means that for an observer on the surface of the Earth, an object in geosynchronous orbit returns to the same position in the sky after a period of one sidereal day. Over the course of a day, the object's position in the sky traces out a path, typically in the form of a figure eight. Its precise characteristics depend on the orbit's inclination and eccentricity.

A special case of geosynchronous orbit is the geostationary orbit, which is a circular geosynchronous orbit at zero inclination (that is, directly above the equator). A satellite in a geostationary orbit appears stationary, always at the same point in the sky to ground observers. Popularly, or loosely, the term “geosynchronous” may be used to mean geostationary. Specifically, geosynchronous Earth orbit (GEO) may be a synonym for geosynchronous equatorial orbit, or geostationary Earth orbit.

The altitude of this platform would be approximately 35,000 km. The satellite platform would be placed into this orbit by a combination of a booster which would place the satellite into an elliptical orbit where the on-board propulsion system would take over and complete a series of impulsive apogee burns to circularize the orbit. The cycle time and cost for such a system is typically 40 months and USD 400 million. A substantial portion of this cost is for insurance to cover losses because of booster failure. Design life is typically 15 years, but with the introduction of a high efficiency electric propulsion system, this life span can be significantly extended, or a less capable booster—a lower-cost booster—could be used and traded for extended life. See Figure 29 and Table 8. One of the benefits is constant vigilance of an area of interest. Some disadvantages are the long development time and higher cost.

We are retaining this option for the trade analysis despite it not meeting the cost requirements because of other benefits, namely the ability to have constant coverage.[106][109]

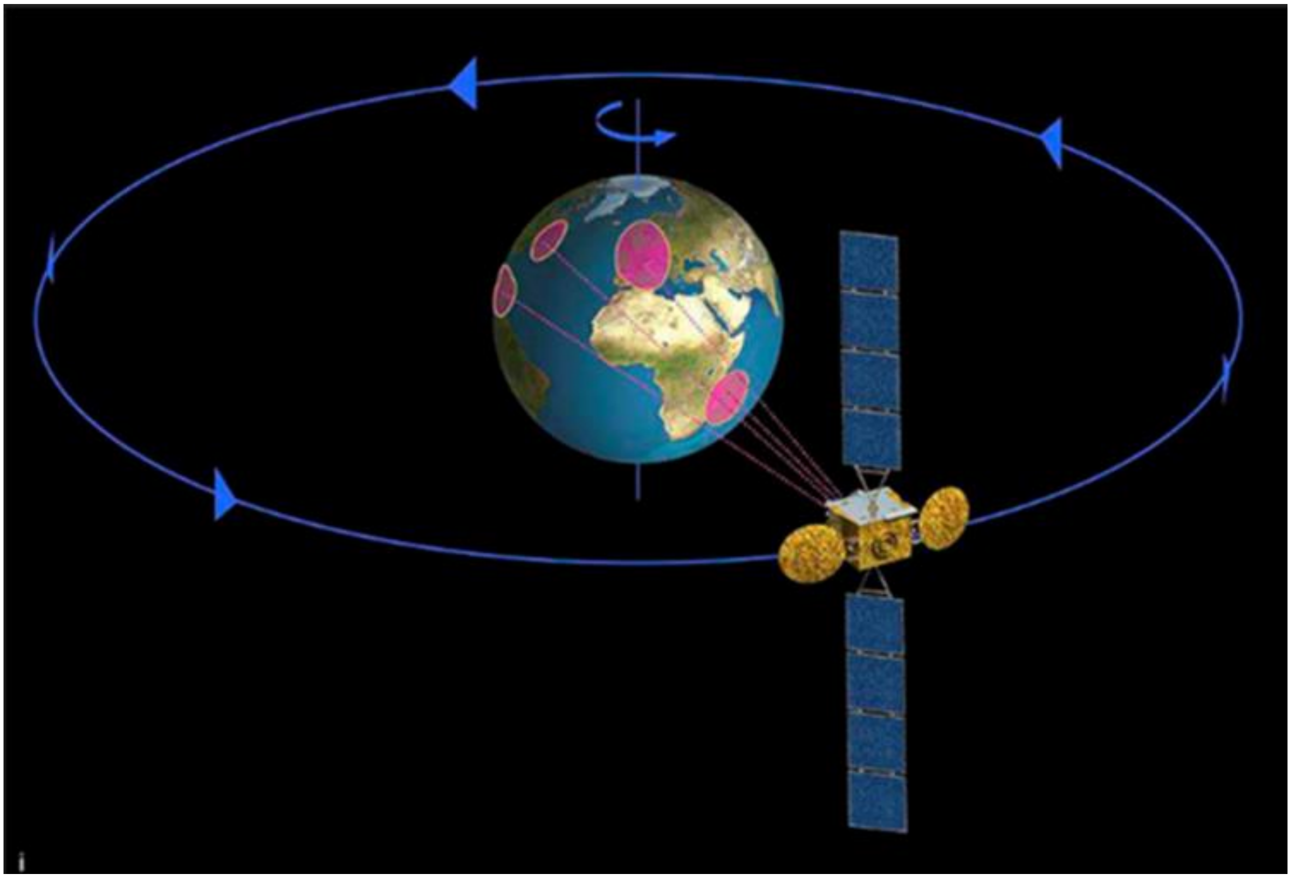


Figure 29: Geosynchronous earth satellite
(https://thecuriousastronomer.files.wordpress.com/2014/11/geostationary_orbit.jpg

Table 9: GOES-15 Characteristics (http://noaasis.noaa.gov/NOAASIS/ml/genlsatl.html

GOES-15 characteristics	
Main body:	2.56 m (8.08 ft) by 4.6 m (15.0 ft) by 2.9 m (9.4 ft)
Solar array:	Length - solar array: 8.2m (26 ft 9 in) Width - Antenna: 2.25 m x 3.37 m (7 ft 4 in x 11 ft)
Weight at liftoff:	7,136 lbm (3,238 kg)
Launch vehicle:	Delta IV
Launch date:	04 March 2010, Cape Canaveral Air Station, US - FL.
Orbital information:	Type: Geosynchronous Altitude: 35, 780 km (22, 233 statute miles) Period: 1,436 minutes Inclination: 0.180087 degrees
Sensors:	Imager Sounder Space environment monitor (SEM) Solar x-ray imager (SXI) Data collection system (DCS)

Polar Orbiting Satellite System (LEO) Option

A polar orbit is one in which a satellite passes above or nearly above both poles of the body being orbited (usually a planet such as the Earth, but possibly another body such as the moon or sun) on each revolution. It therefore has an inclination of (or close to) 90 degrees to the equator. A satellite in a polar orbit will pass over the equator at a different longitude on each of its orbits. A satellite can hover over one polar area much of the time, albeit at a large distance, using a polar, highly elliptical orbit with its apogee above that area.

The altitude of this platform would be approximately 800 km with a period of 90 minutes. The satellite platform would be placed into this orbit by a booster which would directly inject the platform into a polar orbit. Less sophisticated propulsion systems are required on this platform because there is natural precession due to the rotation of the earth. The cycle time and cost for such a system is typically 30 months and USD 200 million. A sizable portion of this cost is for insurance to cover losses because of booster failure. Design life is typically 3 to 5 years. See Figure 30 and Table 10. One of the benefits is higher image resolution of an area of interest. Some disadvantages are the long development time and relatively higher cost.

Similarly, we are retaining this option for the trade analysis despite it not meeting the cost requirements because of other benefits, namely image resolution over an area of interest. This option usually requires multiple assets to meet the latency requirement. As one asset moves away from the coverage area, another must approach to continue the coverage. [110]

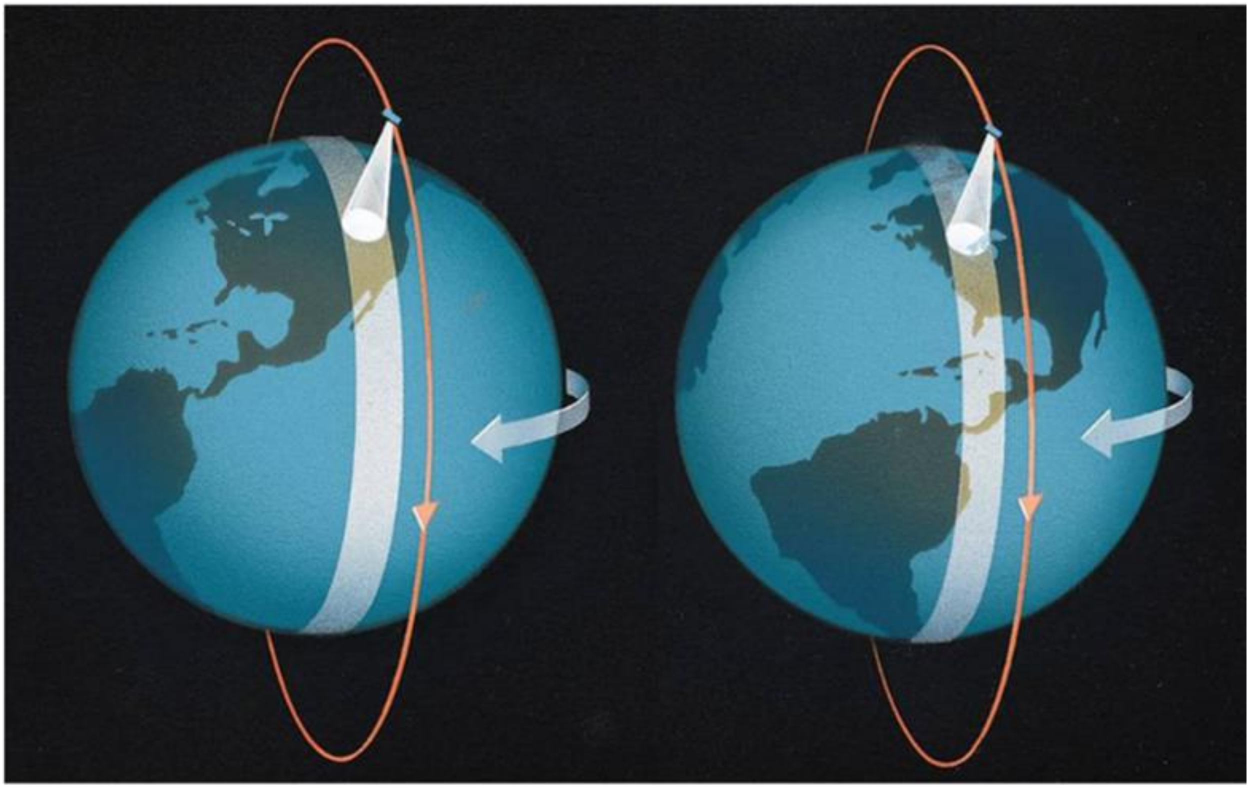


Figure 30: Polar Orbit (http://apollo.lsc.vsc.edu/)

Table 10: NOAA 19 Characteristics (http://noaasis.noaa.gov/NOAASIS/ml/genlsatl.html)

NOAA-19 characteristics	
Main body:	4.2 m (13.75 ft) long, 1.88 m (6.2 ft) diameter
Solar array:	2.73m (8.96 ft) by 6.14m (20.16 ft)
Weight at liftoff:	1419.8 kg (3130 pounds) including 4.1 kg of gaseous nitrogen
Launch vehicle:	Delta -II 7320-10 space launch vechicle
Launch date:	06 February 2009, Vandenburg Air Force Base, US - CA.
Orbital information:	Type: sun synchronous Altitude: 870 km Period: 102.14 minutes Inclination: 98.730 degrees
Sensors:	Advanced very high resolution radiometer (AVHRR/3) Advanced microwave sounding unit-A (AMSU-A) Microwave humidity sounder (MHS) High resolution infrared radiation sounder (HIR S/4) Solar backscatter ultraviolet spectral radiometer (SBUV/2) Space environment monitor (SEM/2) Search and rescue (SAR) repeater and Processor Advance data collection system (ADCS)

Hosted Payload Option

A sensor complement payload would be integrated onto a host satellite to be placed into a GEO or LEO orbit Figure 31. The orbital period would be approximately 100 minutes to approximately 24 hours. The altitude would be approximately 700 km to 35,000 km mean sea level. The system cost is approximately USD 4 million. Development and initial deployment time are approximately 30 months. Since this is a piggyback system, development/deployment time driven by total design life would be approximately 5 years to 15 years. The benefits of this type of system would be:

- Low cost.
- Shorter time to orbit.
- More resilient architecture.
- Increased access to space.

Figure 31: Hosted payload satellite system (https://www.harris.com/solution/hosted-payload-solutions)

Unmanned Aerial Vehicle (UAV) Option

An unmanned aerial vehicle (UAV), commonly known as a drone or an unmanned aircraft system (UAS), is an aircraft without a human pilot aboard. The flight of UAVs may operate with various degrees of autonomy, either under remote control by a human operator or intermittently autonomously by onboard computers.

Compared to a crewed aircraft, UAVs are often preferred for missions that are too "dull, dirty, or dangerous" for humans. They originated mostly in military applications, although their use is expanding in commercial, scientific, and recreational fields, among other applications. They are used in policing and surveillance, aerial photography, agriculture, and drone racing. Civilian drones now vastly outnumber military drones, with estimates of over a million sold in 2015.

A terrestrial system of either rotorcraft or fixed-wing configurations with no human pilot on board the aircraft is the leading concept after very preliminary analysis. The system's architecture would incorporate functionality, which would allow varying degrees of autonomy—remote control or intermittent autonomous control by onboard computers.

The benefits of this type of system would be:

- Lower cost.
- Shorter time to deployment.
- More resilient architecture.
- Minimal infrastructure required.

The forest wildfire detection UAV system—named "Fire Crow"—will be similar in basic architecture to transitional UAV (see Figure 32), due to the launch and landing flexibility requirement.

2nd concept

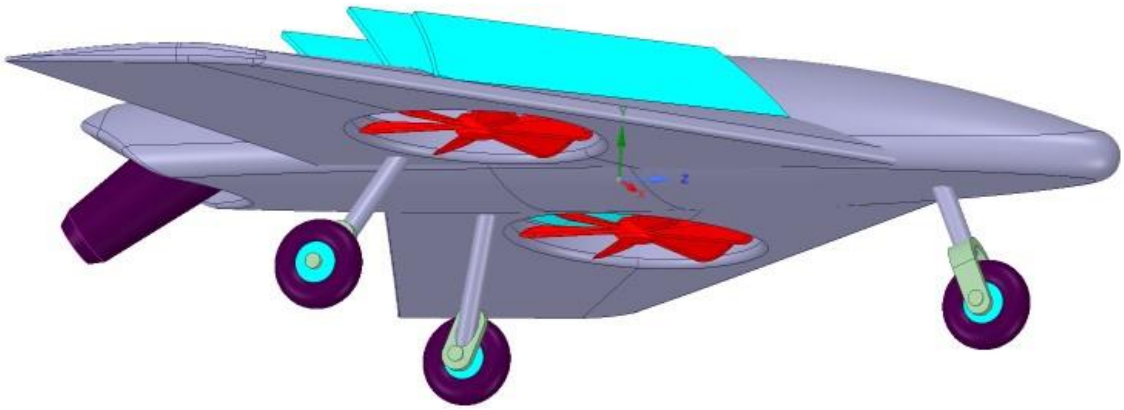


Figure 32: H-UAV Concept - Hybrid Propulsion

First level Trade Analysis
Trade Analysis

We conducted a first level trade analysis given the basic requirements of the fire detection and communication system. Since the system is primarily geared to counties and or lower-budgeted operators, affordability is one of the driving requirements, followed closely by detection time, operational flexibility, and cybersecurity. We calculated the cost for the various concepts based on cost/pound mass data gathered from sources found on the World Technology Evaluation Center's website. We derived the affordability index from a ratio of the projected cost and the cost target (3 million USD) for the system. We applied weighting factors for the other key measurements which depended on the importance of those measurements to system effectiveness. Finally, we applied a single algorithm to arrive at a final score for each of the concepts. From the scores listed in Table 4, the UAV rotor-wing concept appears to be leading. As indicated by the results presented in Table 4, the fixed-wing UAV concept was a close second choice but ultimately lost to the rotorcraft because of the added operational flexibility that a rotorcraft configuration offers. The fixed-wing UAV requires additional infrastructure such as a mobile launch and recovery system or a runway system to land and take off, whereas a rotorcraft could launch and land from a remote location with minimal infrastructure required.

Table 11: Trade Analysis

Measurement	Rank	Concept options												Comments
		Satellites						UAVs						
		GEO	normal	LEO	normal	Hosted Payload	normal	Rotorcraft	normal	Fixed-wing	normal	Blimp	normal	
Cost (USD K)		USD 291,420		USD 281,700		USD 44		USD 120		USD 100		USD 90		USD8000/lb - target cost USD120K
Affordability	10	0.0103	0.0130	0.0106	0.0107	68.6295	0.0686	25.00	25.00	30.00	30.00	33.33	33.33	target less USD3 M
Detection	8													
Loiter		1	1	0.5	1	1	1	0.5	0.5	0.75	0.75	1	1	weighting factor
Acuracy		0.75	0.75	0.75	0.75	0.75	0.75	0.95	0.95	0.95	0.95	0.95	0.95	weighting factor
Flexibility	9													
Weight		3238	0.0003	3130	0.0003	50	0.02	75	0.013	70	0.014	300	0.003	weight in kilogram - sat weight from large sat trends www.wtec.org
Deployment		1	1	1	1	1	1	15	15	0.5	0.5	0.5	0.5	weighting factor -Take off / Landing
Cybersecurity	7	2	2	2	2	1.5	1.5	1	1	1	1	1	1	weighting factor - Ability to prevent hacking and malicious use
Score			37		37		34		404		325		360	

Affordability

Total system cost and affordability are key drivers for the trade study. To that end, the supposition is that there are three phases of affordability that we must address as part of the trade study. Further, affordability indices will vary and may increase as the importance of a system increases. Research results show we can dedicate 2% to 22% of available budget to mitigation activities and given the damage cost of wildfires—in the tens of billions—budget allocations will be higher in importance and will justify a higher affordability index.

Phase I is a generic phase/definition of affordability, which simply states that a system is affordable if it meets the cost/schedule and technical objectives as defined and agreed to by all major stakeholders at the beginning of the system development activities. “Systems developed for wildfire mitigation must meet user needs as evidenced by operational effectiveness and operational suitability and must be affordable” (Dallosta and Simcik 2012).

Phase II (borrowing from the housing/banking industries) states that a system is affordable if its total cost is below prescribed threshold value or percentage of available budget. According to the National Association of Realtors website, a home is affordable if the carrying cost (mortgage) is less than 15% - 22% of the consumer’s monthly budget (take home pay).

The intention Is to target counties as potentials customers for the UAV fire mitigation systems. To that end, we will use three million USD as an affordability target. This represents less than three percent of the midpoint of the range of available budget. Research results show budget by way of grants and insurance liabilities paid out in San Diego County US-CA, as an example, is from three million USD to as much as 375 million USD.

Phase III relates to the net value add of a system after it is developed and deployed. Simply, if a system can deliver for its intended operators—cost avoidance more than the cost of development and sustainment—then that system must be affordable. The intention would be to use a return multiple index greater than 15. This index and approach are leveraged from certain sectors of the aerospace industry. The procedure was developed to differentiate which affordability initiatives to carry forward and fund by comparing the cost of the initiative to the projected savings/cost offsets that initiative will yield.

Finally, one of the primary objectives of the trade study is to objectively arrive at the best solution for mitigating wildfires by trading a collection of performance measures including total system cost. In this sense, absolute affordability, while certainly very important, is not central to the continuation nor completion of the trade study.

See Chapter 4 – Figure 46, for popular UAVs and the “Fire Crow UAV” system which is the subject of discussion for the UAV portion of the trade study.[104][105]

UAV Concept of Operations

The UAV would be semiautonomous, with flexible landing and takeoff capabilities. An operator in the highly vulnerable and hard to navigate forest area of interest would pilot this UAV remotely. Upon arriving at this area of interest, the UAV would then fly a flight plan autonomously, utilizing LiDAR technology to collect data which will then be communicated to a base station. In the event of a positive detection, further data reduction will be completed, and the information will be directed to wildfire mitigation services.

Flight path modification would be driven by a review of history of wildfires for that area. They will also gather information from other sources to minimize detection time and avoid areas where the probability of occurrence is low.

It is important that the system incorporates cybersecurity measures around command-and-control communication. This will help to ensure that the operators maintain reliable and continuous control of the UAV to prevent interception and redirection for malicious use.

In addition to the obvious damage to intelligence and loss of very expensive equipment, there can be the added loss of enabling technological advancement of an adversary. Data collected and processed would be encrypted as part of a layered security approach so that if an adversary were to access the data, it would be of little use.

Network security would be implemented using Simple Network Management Protocol (SNMP). It will use a manager on a server, which will maintain a management information base (MIB) and an “agent” installed on monitored devices.

The UAV sensor information processing in the second enclave on board the UAV would be protected by UTM and endpoint security and an intrusion detection/prevention system (IDS/IPS).

One example of what could happen if hackers took control of a UAV was the Iran hack of the United States UAV (RQ-170 Sentinel). There are claims that months before the hacking event, a virus was implemented onto the drone, allowing easier jamming of the GPS signal, hijacking, and redirecting of the UAV. In addition to damage of intelligence and loss of very expensive equipment, there was the added loss of enabling technological advancement of an adversary.

Another concern is that with the increasing use of UAVs, there would be increased attempts to hack and take control of commercial UAVs for malicious purposes. With only a small probability of success, the results of losing control of UAVs to parties for malicious intent could have severe consequences for industries like commercial aviation and others.

The primary users of the "Fire Crow" will be those agencies currently employed to detect and fight wildfires. Some examples are the Cal Fire and Colorado Departments of Forestry. The information collected could be of use to other conservation departments and/or institutions interested in modeling forest fire behavior.[96]

Trade Study Conclusion

Research results to date show that a Transitional UAV is the leading concept to move forward with into the detailed design stage for detecting and communicating the location of wildfires. Work will continue with initial concept definitions for each of the concept options, along with initial risk analysis for the leading concepts. Although the author acknowledges the shortfalls of early focus of a seemingly obvious concept, the risk analysis and function allocation and initial block diagram development focused on the UAV concept utilizing a LiDAR sensor to collect data over an area of interest.

Benefits of UAV option are:

- Lower cost.
- Shorter time to deployment.
- More resilient architecture.
- Minimal infrastructure required.

As the research continues, other options may surface as best, or perhaps a combination of options might be better than any singular one. As an example, there may be a system architecture where information from existing LEO and GEO satellites could be used in concert with a UAV system to fine-tune the search area and thereby reduce the time required to surveil and report back on a possible wildfire.

Chapter 4

Integrated MBSAP and Design Space Exploration applied to Autonomous UAV based Wildfire Detection and Communication

Summary

A previous Model-Based Systems Architecture Process (MBSAP) trade-study compared land, air and space-based wildfire detection and communication solutions to conclude that the winning architecture for a wildfire detection and communication system essentially required a low-cost, truck-launched, locally owned, and operated H-UAV with VTOL and thrust vectoring capability.[7] This paper focusses on a design space exploration (DSE) method that is integrated into the MBSAP such that the stakeholder needs, and requirements (mission, cost, weight, range, performance, and operation) directly drive the preliminary sizing and selection of all major UAV systems (Airframe, Hybrid Electric/ Gas turbine powerplant, Flight Controls, Lift Fans, Vectoring Nozzle and Sensor package payload).

Hence, the systems thinking advantages of integrating DSE with MBSAP is that we have a coupled architecture / executable model that quickly identifies the feasible regions of the design space in addition to identifying the sensitivities around any points contained in it. The DSE method itself is an integration of disciplinary solvers, constrained numerical optimization and Monte-Carlo based sensitivity analysis. The DSE has the key advantage of finding the optimal feasible size, weight, cost, and range of the UAV in the design space, in addition to the sensitivity of the optimal design to key Battery, Propulsion and Airframe design drivers that include technology measures. This helps answer questions

like: which approach has more leverage on range or specific cost $/(kg.km): increasing the battery energy density, or the aerodynamic efficiency of the airframe?

The optimal design with today's commercially available technology weighs 47 kg, cruises at 295 km/h, loiters at 167 km/h, costs ~$124000 (2020 $'s) and carries a useful payload (sensor package) of 6 kg 133 km. The weights and dimensions of the fuselage and wings of this UAV are such that they can easily be transported to location on a truck by a driver that also assembles, launches, and retrieves the UAV after landing. We believe it should easily be possible to package 3 such UAVs in the back of a mid-size truck so that local ownership and operation of a small fleet shall be feasible.

This chapter describes the DSE method in addition to visualizing what the hybrid electric/gas turbine propelled optimal UAV looks like, how practical it is and how sensitive its measures of effectiveness are to improvements in various enabling technologies such as improvement in battery energy density.[1][31][32][33] Furthermore, a relative comparison is made to discover when a E-UAV will become feasible and break even with a H-UAV in terms of specific cost ($/kg.km) for the same wildfire detection and communication mission.

Increasing Impact of Wildfires

Wildfires have been on the increase in frequency, duration, and intensity worldwide. Climate change, drought and other factors have not only increased the susceptibility to wildfires but have also led to increase the duration of the season. In the Western United States, wildfires can release as much carbon dioxide into the atmosphere in a week as all the automobiles in the region for an entire year.[80][81] Overall study estimates that fires in the contiguous United States and Alaska release about 4 to 6% of the nation greenhouse gases released through burning fossil fuel or about 290 million metric tons of carbon dioxide a year.[100]

In 2021 there were 58,985 wildfires that burned 7,125,643 acres. The total number of fires and acres burned in 2021 were like both the five year and ten-year national averages, However, 2021 was a notably active year for certain Geographic Areas. 2018 was the deadliest and most destructive on record in California. Some 8527 fires burning an area of 1,893,913 acres which was the largest amount of acreage recorded in a fire season. The fires have caused more than USD 3.5B in damage including USD 1,792 M in fire suppression costs. Cal Fire alone spent USD 432 M on operations. [101]

Overview of the Approach

Using a Model-Based Systems Architecting Process (MBSAP) [90][92][102][103][104][105], the stakeholders operational, economic and performance needs were captured for a locally operated cost-effective solution to detect wildfires. A trade study of multiple land-, air- and space- based solutions resulted in a winning architecture [7] that is a small fleet of autonomous VTOL H-UAVs pictured in Chapter 2 – Figure 21

A brief visualization of the H-UAV mission is shown in Chapter 2 – Figure 14. After much multidisciplinary analysis and optimization, we discovered that although all segments drive a significant level of detailed requirements, only a fraction of the mission (segments, 1,2 and 5) were major drivers for the preliminary sizing of the airframe and propulsion system (see the highlighted list of parameters that these segments determine in the figure – Chapter 2 Figure 14.

Finding an optimal feasible point in the constrained multi-dimensional nonlinear design space that includes aerodynamics, propulsion, electric motors, lift fans, battery, gas turbine, generator and vectored thrust would normally require a multivariate multi-objective numerical optimization routine that would be very sensitive and impractical due to a very large set of highly coupled nonlinear equations with many independent variables, constraints, and figures of merit.[70]

We therefore developed an analytical sequence or recipe of 18 interconnected contributing analysis (CA's), several of which include an internal solver, as listed in the CA table in Chapter 2 – Table 7

The CA's make heavy use of semi-empirical data or known information about UAV's and key components reported in the literature. The proper sequencing of the interconnected CA's then reduces the complexity of the generic optimization problem into finding a feasible sizing so that the interconnected Climb, Loiter Range and Weight optimizers are satisfied, as shown in Figure 33**.** [8][16][22][26][38][55][66][67][116][117][118]

Once the optimizer was V&V'ed (see later section), then it was placed inside a Monte-Carlo loop to rank the impact of key aerodynamic, climb, electric, fan and battery design drivers on cost, range, and weight, as shown in – Figure 33 and 34.

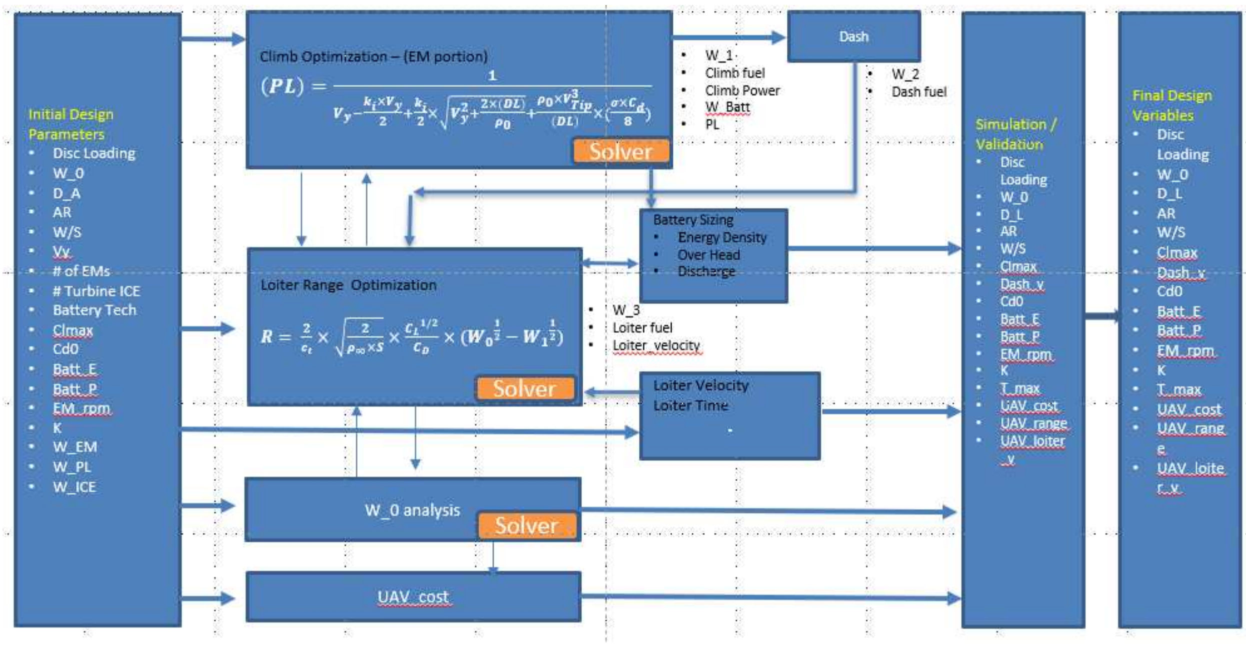


Figure 33 Simplified optimization method

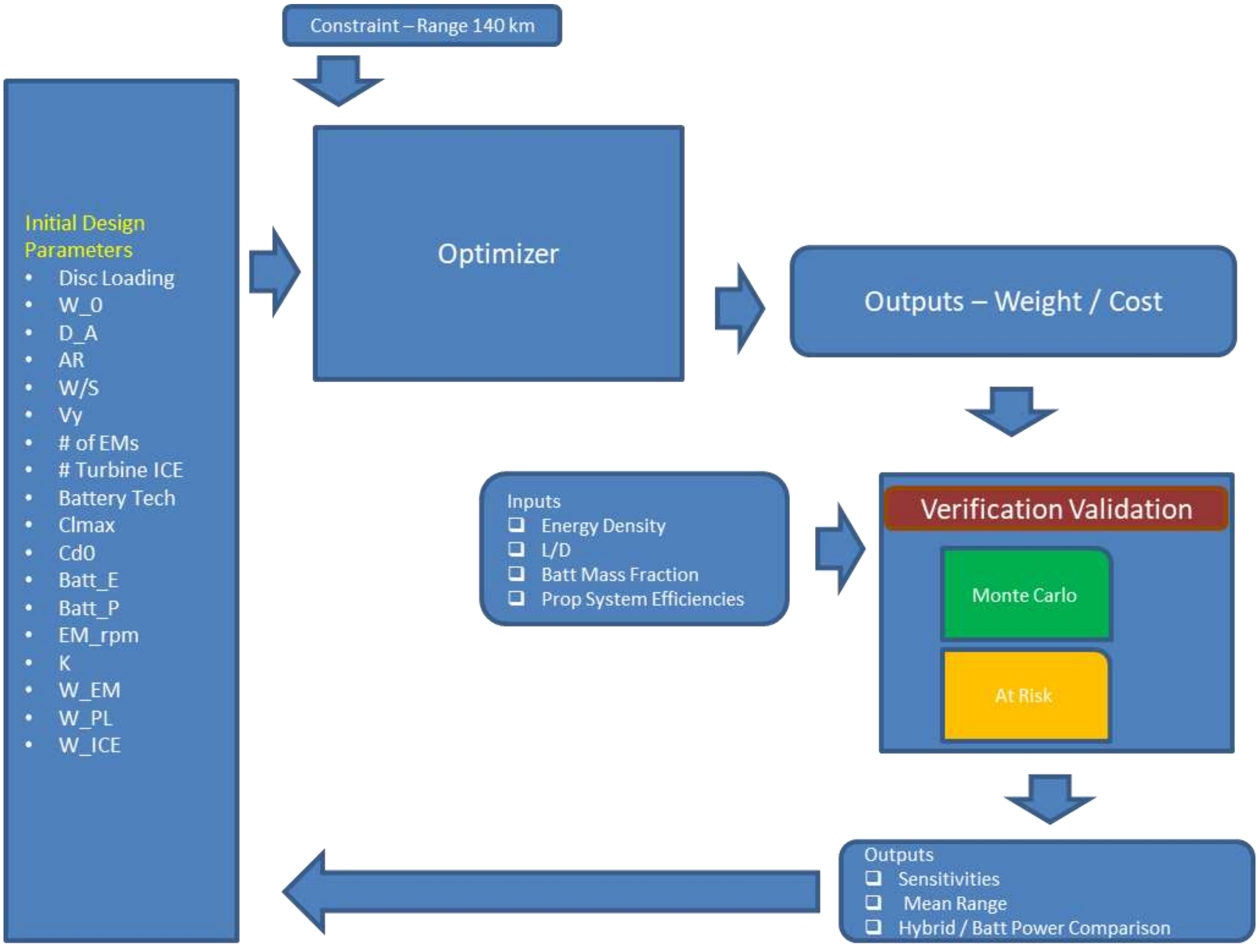


Figure 34: Optimizer wrapped inside a Monte Carlo Loop (Executable Model)

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Statistical assumptions for the distribution of design drivers used as inputs into the Monte-Carlo analysis are shown in Figure 35. These were based on current, most-likely, and foreseeable future values included in the literature, supplier data sheets, and expert opinions stated at interviews.

Example output from the Monte-Carlo study are shown in Figures 36 & 37. The former shows that the E- UAV range needs significant improvement to break-even with the H-

UAV. The tornado chart shows that for the H-UAV, battery energy density has less impact on range than 3 other factors.

In summary, our DSE approach integrates a particular analytical recipe of 18 CA's together with solvers and constrained optimization routines to identify the best design point. Once a design point is found, we wrap the above inside a Monte-Carlo loop to compare the relative advantages of UAV configurations (Electric versus Hybrid) in addition to finding the sensitivity of the design point to design drivers from operation, sizing, and technology measures.

Note that *not all* Monte-Carlo simulations result in practical designs or a design for which the solvers in the optimization method of Figure 37 converge to a solution. To filter out the bad Monte Carlo iterations, we specified solver tolerance constraints and practical design constraints, so the results included in this paper, such as the Range distribution comparison in Figure 36 or the tornado chart in Figure 37 have already filtered out the bad Monte Carlo iterations.

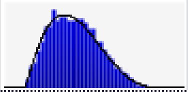
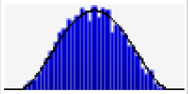
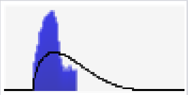
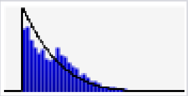
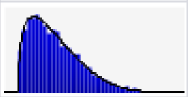
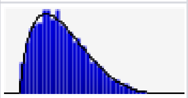
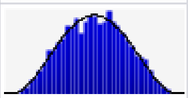
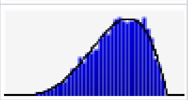
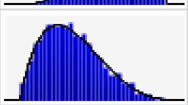
Name	...	Graph	Minimum	Maximum	Mean	Mode	Median	Std. Dev...	1%	99%
WTO (kg)	...		39.117	63.755	48.714	47.186	48.376	4.758	40.190	59.849
Wing Area (m^2)	...		1.56106	2.03956	1.79395	1.80290	1.793...	0.09438	1.59583	1.99211
Vy (m/s)	...		4.6298	12.0920	7.7734	7.6264	7.6047	1.7205	4.8627	11.8753
L/D	...		9.967	23.773	13.373	10.062	12.976	2.567	10.007	20.437
BattED (W.h/kg)	...		245.56	697.17	369.16	309.52	353.11	85.24	250.34	608.49
BattMF	...		0.049352	0.089123	0.061049	0.055900	0.059...	0.007148	0.050064	0.0799...
PropEff	...		0.69123	0.81020	0.75033	0.76153	0.750...	0.02424	0.70040	0.80097
Batt Specific Cost ($/kg)	...		36.662	65.972	55.173	58.006	55.777	5.923	40.443	65.100
Jet Fuel Specific Cost ($/kg)	...		0.57981	1.30453	0.83658	0.81141	0.821...	0.14187	0.59856	1.20111

Figure 35: Distribution of Design Drivers including Technology Measures

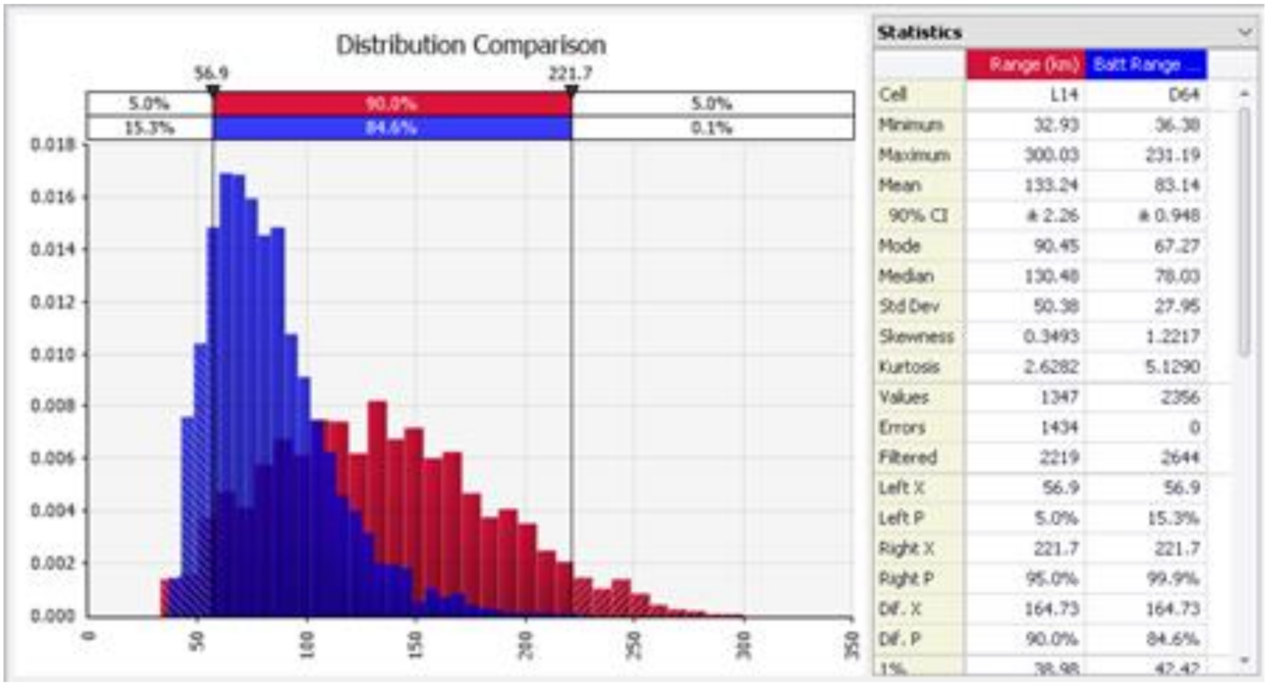


Figure 36: Range comparison between Fully Electric and Hybrid Electric/Gas turbine UAV

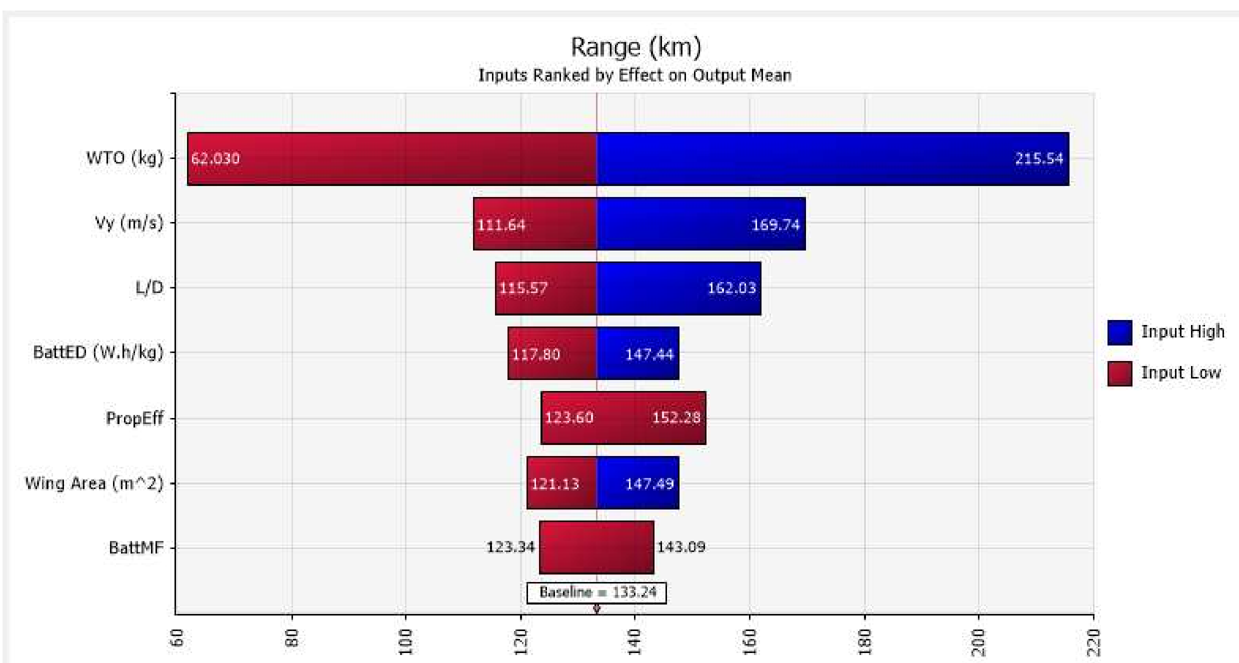


Figure 37: Tornado chart ranking the biggest design drivers for range of H-UAV

Mission Details

The basic mission of the H-UAV requires a small fleet of locally owned and operated H-UAVs that are transported to a (remote) take-off location such as the border of a town or a remote neighborhood or the edge of a dense forest by a 4X4 mid-size truck. The cargo bay shall conveniently package a fleet of 2 to 3 H-UAV's by breaking each H-UAV into 3 main sub-assemblies: 2 wings and a fuselage. The subassemblies shall be vertically mounted to the cargo bay and tied down, using foam and other packing material in-between the subassemblies for protection during transport.

The operator unpacks, assembles, and fuels each H-UAV that does a self-check (assembly switches, fans, battery, control surfaces, gps coordinate, communication link, etc.) before the autonomous mission sequence shown in Figure 2 begins.

Vertical take-off (if at a remote location and not an airstrip) is achieved by a combination of wing mounted lift fans and vectored thrust from the gas turbine. Once airborne, the H-UAV transitions to forward flight and dashes quickly to the area of interest: i.e., predetermined coordinates and altitude where loitering and the surveillance flight pattern starts. The flight pattern would guarantee adequate area coverage starting from diagonally opposite positions over the area of interest. Flight pattern and area coverage would be optimized based on history and preloaded area topography to ensure that the UAVs fly the most optimal coverage pattern. If a wildfire is detected using a suite of sensors (LiDAR, IR, Video Cam), the UAV shall communicate the wildfire location to the base station so that fire mitigation services could be deployed. The UAV(s) shall optionally also transition to hover mode and stare at the location to provide additional or updated information to fire mitigation services. If a wildfire is not detected, the UAVs shall complete the surveillance mission and return to the truck or the airstrip.

While loitering the H-UAV has several autonomous functions:

- Navigating the pre-loaded fire probability and topology maps.
- Scanning a sector along the flight path to
    - update the pre-loaded fire probably map based on data from the sensor package.
    - update the pre-loaded forest topology map based on data from the sensor package.
    - decide whether to lower altitude to focus on an area with a higher probability until the criteria for actual fire detected is met.
    - decide whether to transition to hover to focus on a location.
- communicate a video frame together with the GPS location of frame boundaries and center, direction, and speed of fire in the frame.
- Avoid other fleet members, flying objects and large birds.
- Monitor for new operator inputs such as abort mission, updated topology maps, updated fire probability maps, updated landing location etc.

Figure 38 shows an example of the useful actionable information that the H-UAV sends back to the operator or base station.

Figure 38: Photo of detected wildfire with location and speed information communicated to base or operator. Source: Tim Middleton from Colorado State University

1st Gen Optimal Design

Optimal design here means optimal for the currently available level of technology and requirements (including constraints) imposed by stakeholder needs, operational scenarios and mission.

Figures 39 and 40 show the 1st Gen concept in hover, climb and transition to forward flight modes (first 2 phases of the mission shown in Chapter 2 – Figure 14) where lift is provided purely or partially by lift fans and vectored nozzle. The design matches the optimal design point in this configuration, the doors on top of the wing open to allow flow through the lift fans and the nozzle is pointing downwards at an angle of zero to 90 degrees relative to the fuselage central axis. The hole on top of the fuselage is the air intake for the gas turbine that is inside the fuselage.

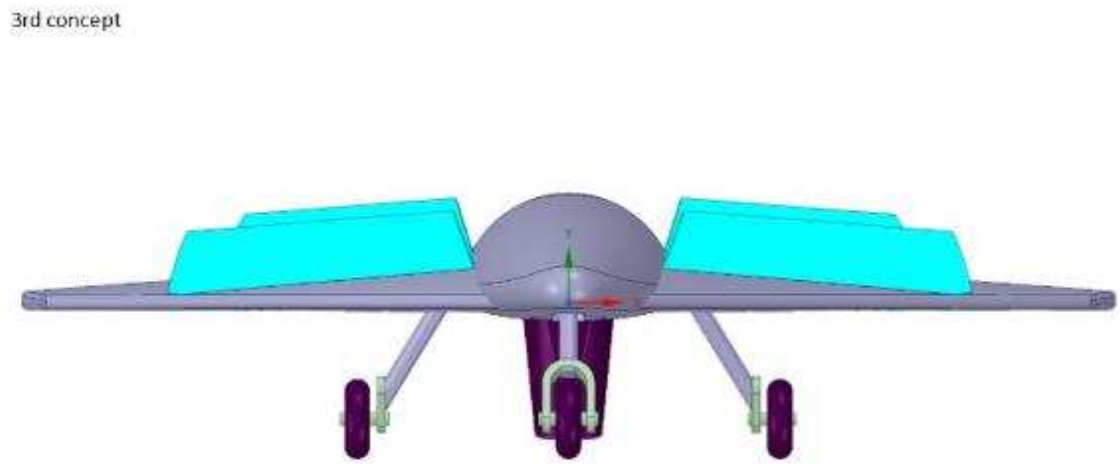


Figure 39: Frontal View of 1st Gen Optimal Design in launch configuration

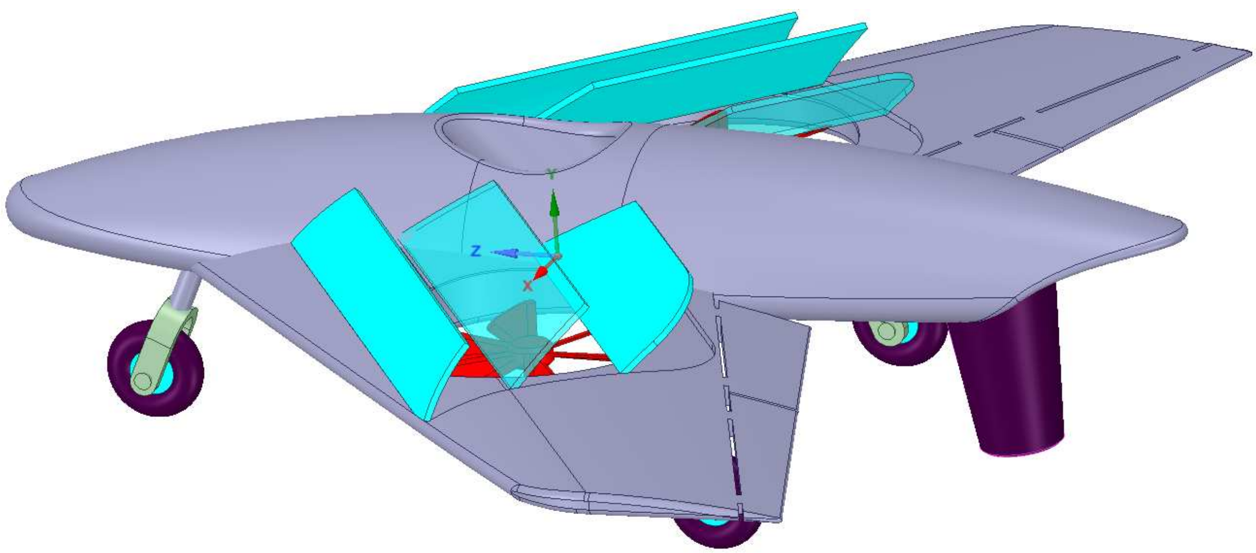


Figure 40: 1st Gen Design in Launch configuration

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Figure 47 shows the sized concept in forward flight after transition in (phases 3 to 7 of the mission shown in Chapter 2 – Figure 14). Here the fan doors on top of the wing are closed, so that the top of the wing has a fixed wing shape; Nozzle is aligned with the fuselage;

and landing gear retracted. So, the UAV is in its most aerodynamically efficient configuration in the loiter phase where the UAV spends most of its mission time before returning for a vertical landing in a remote location or an airstrip if one is available.

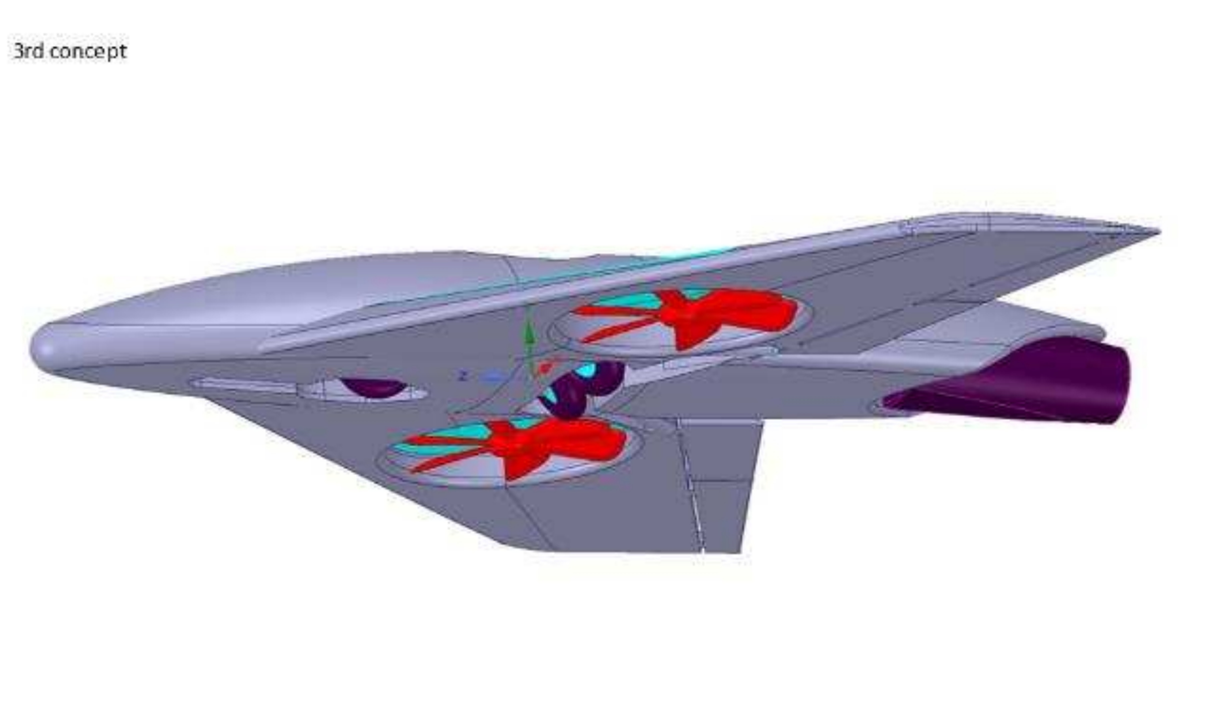

Figure 41: 1st Gen Optimal Design in Dash and Loiter Configuration

The 1st Gen design weighs 47 kg, cruises at 295 km/h, loiters at 167 km/h, costs ~$124000 (2020 $'s) and carries a useful payload (sensor package) of 6 kg 133 km. All the major subsystem sizing and selection (airframe, hybrid electric/gas turbine propulsion, nozzle, battery, landing gear, flight controls etc.) were determined by the DSE method explained earlier.

For the H-UAV, optimizing the mass is a big deal (i.e., it has high leverage on all cost and performance measures). The 1st Gen design has the following component weights.

Table 12: H-UAV Component Weights

Total Weight (kg)	**46.64**
Fuselage Mass (kg)	2.17
Wings Mass (kg)	3.86
Empenage Mass (kg)	0.342
Landing Gear (kg)	4.77
Airframe Mass (kg)	**11.14**
Fuel Mass (kg)	7.08
Battery (kg)	1.87
Storage Total	**8.96**
Gasturb Mass (kg)	2.29
Lift EM (kg)	1.44
Lift Props (kg)	0.19
Ducting (kg)	4.00
Propulsion Mass (kg)	**7.92**
Flight Controls Mass (	**12.62**
Payload Mass (kg)	**6.00**

The optimal value of component masses is the result of the DSE optimization process of Figure 29 and explained in more detail later in this chapter.

DSE Capability: Coupled Architecture

Our DSE method enables a Coupled Architecture / Executable Model since it is integrated with the MBSAP. This means that it is relatively easy to discover the impact of changing stakeholder needs to UAV architecture and vice versa.

For example, we can answer some difficult questions like: Can we beat the optimum? Figure 8 shows that we can practically extend the range of the UAV by 100 km by scaling up (larger dimensions, weight, and larger fuel tanks etc.) and adjusting the vertical take-off speed. This will result in a larger area coverage per UAV. But now the individual wings and fuselage are heavier and larger so that the operator needs to be capable of carrying and assembling heavier parts. Furthermore, we may no longer be able to package 3 of the larger UAVs in the back of a mid-size truck so the means of land transportation to a remote location or the number of UAVs in the fleet will be impacted. Furthermore, the larger engines required may no longer be easily source-able requiring a purpose made gas turbine that will heavily impact the cost. Are these impacts acceptable? Well, it depends on the stakeholders' needs, operational scenarios and mission.

Another normally difficult question: What if in practice we find that the weight of the Sensor package (containing sensors: LIDAR, IR, Video Camera and pointing mechanism) is 7 kg and therefore larger than the allocated 6 kg. Can we still achieve the same range for the mission? A simple answer might be to save 1 kg elsewhere such as the Airframe, Propulsion and Flight Controls. However, Figure 32 shows that we have at least 3 high leverage directions to compensate for this: larger size, faster vertical take-off velocity and higher L/D through aerodynamic optimization.

Early is the MBSAP, process and operation models are developed and further refined as the architect synthesizes the system in various views.[85][86][87] These become valuable when integrated with trade-studies, DSE, digital twins, and simulations. We call this a coupled architecture because it ensures that the systems structure and behavior stay aligned with or consistent with stakeholder needs, requirements and use cases, when something changes.

As the system develops, there is often the need to evaluate different bounding criteria and answer what if scenarios such as the two example situations cited above. Here the coupled architecture can give the answer quickly if the toolchain is seamlessly integrated. For example, we can change the mission/payload and bounding technology assumptions and recreate all the tornado charts containing actionable information about the optimal design and its sensitivity automatically.

Results, New and (Perhaps) Counterintuitive Findings

Earlier sections already showcased the capability of our DSE approach to find an optimal design for the specific wildfire detection mission, in addition to sensitivity of the measures of effectiveness (cost, weight, range etc.) to major design drivers such as L/D (aerodynamics technology measure) and Battery Energy density (electric technology measure). The main reason this capability is critical is that the design space is non-linear and that cost effective locally operated wildfire detection system has unique stakeholder needs, mission, and operational scenarios. This explain the result that is counter-intuitive to some readers: We cannot simply extend or scale the architecture of an urban package delivery E-UAV to make it suitable for wildfire detection, even if we set the payload requirement to be the same as the wildfire detecting UAV: 6 kg.

The same applies to some other conclusions in UAV related literature. For example, an apparent theme in the UAV literature is that the mission success of a UAV fleet is more sensitive to the intercommunication between the UAVs (and distribution centers) than the architecture of their propulsion system or airframe. This conclusion may be true for large fleets of short-range package delivery UAV's, collaborating in an around urban distribution centers where they can recharge. However, it does not apply to small fleets of H-UAV's mapping remote forests and detecting wildfires cost effectively.

Our previously reported MBSAP integrated trade-study of land, air, and space systems [7] identified the winning architecture where we quickly discovered that the biggest enabler for the mission success was the propulsion system/airframe architecture and not the inter communication between fleet members. Intercommunication and collective intelligence for coordinating a fleet is obviously useful but does not have nearly the same priority as the propulsion system/airframe integration when the purpose is: low-cost locally owned and operated autonomous wildfire detection.

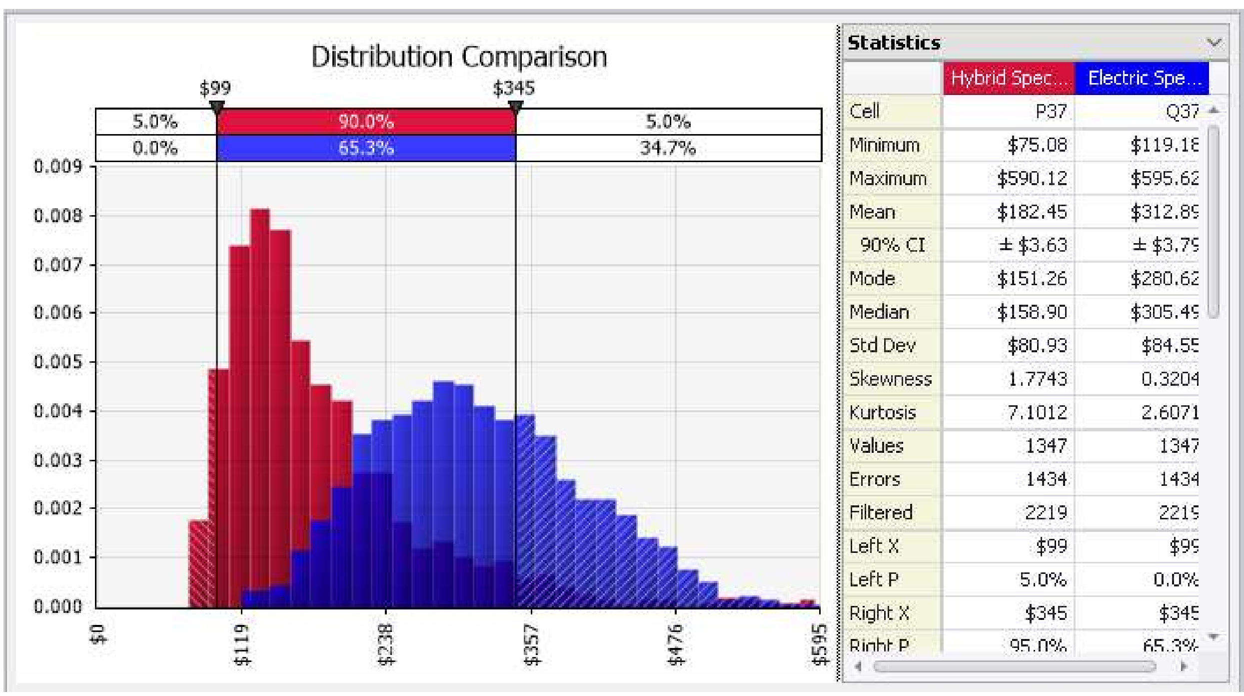

Figure 42: Specific cost $/(kg.km) comparison of H-UAV (Red) Vs. E-UAV

Figure 42 shows that in terms of the cost of carrying a useful payload some distance, the E-UAV (fully electric) is more costly than the H-UAV: 313 versus 182 $/(kg.km). Furthermore, Figure 14 shows that only the most optimistic practical assumption for a future battery density and future battery mass fraction will barely beat the baseline specific cost of current technology H-UAV at 182 $/(kg.km).

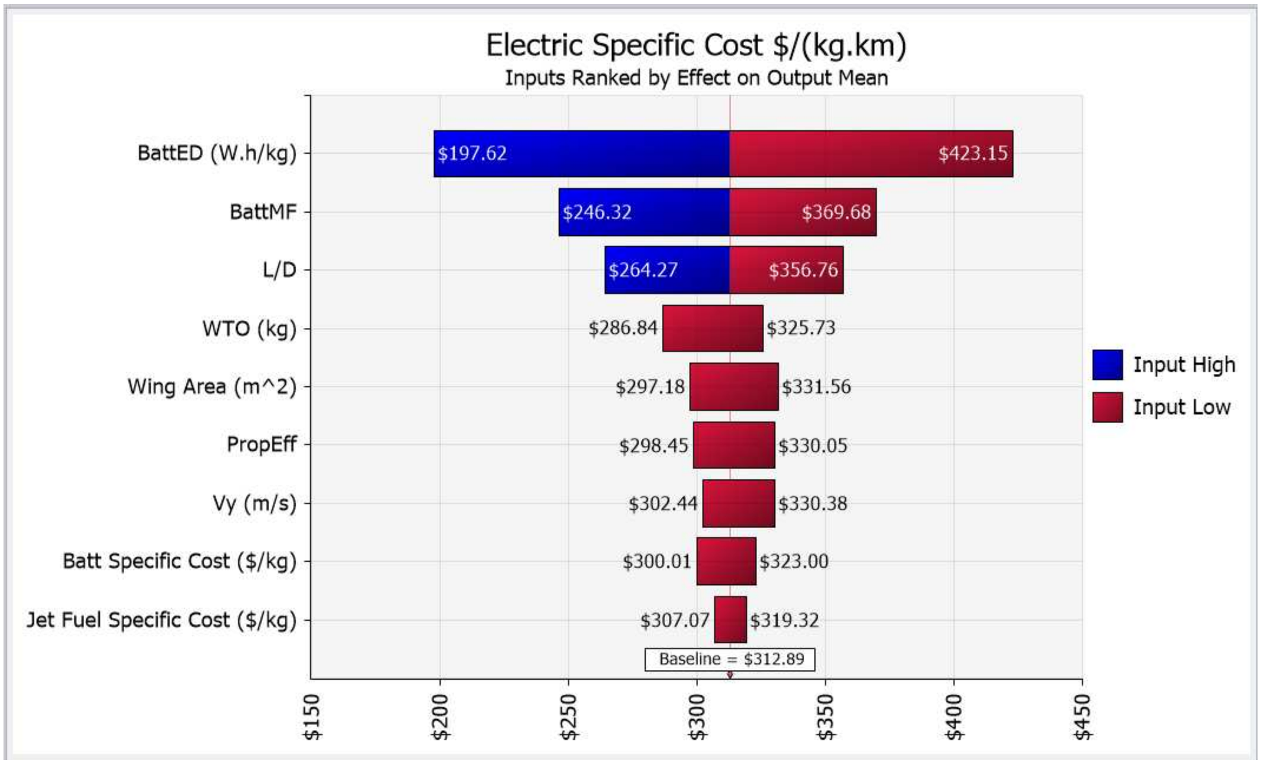

Figure 43: Tornado chart of specific cost drivers for the E-UAV (fully electric)

Figures 43 and 44 show that scaling, vertical take -off speed and L/D ratio have far more leverage on cost of the H-UAV than battery energy density and battery mass fraction have on the E-UAV: in other words, improving the specific cost of the H-UAV is a lot easier than the E-UAV for the purpose of locally owned and operated low-cost wildfire detection.

Some results may be counter-intuitive at first sight. For example, why would increasing vertical take-off speed reduce the specific cost of H-UAV (Figure 44) and not the E-UAV (Figure 43). Well, faster vertical climb allows the H-UAV to transition to the efficient forward flight mode quicker. Quicker climb also reduces the time that the gas turbine is spending in an inefficient part of its operating cycle, saving fuel for the efficient forward flight mode. Note that liquid fuel has orders of magnitude higher energy density than batteries so any wight savings due to operational changes or better technology will translate to Range, Endurance or Specific Cost Benefits

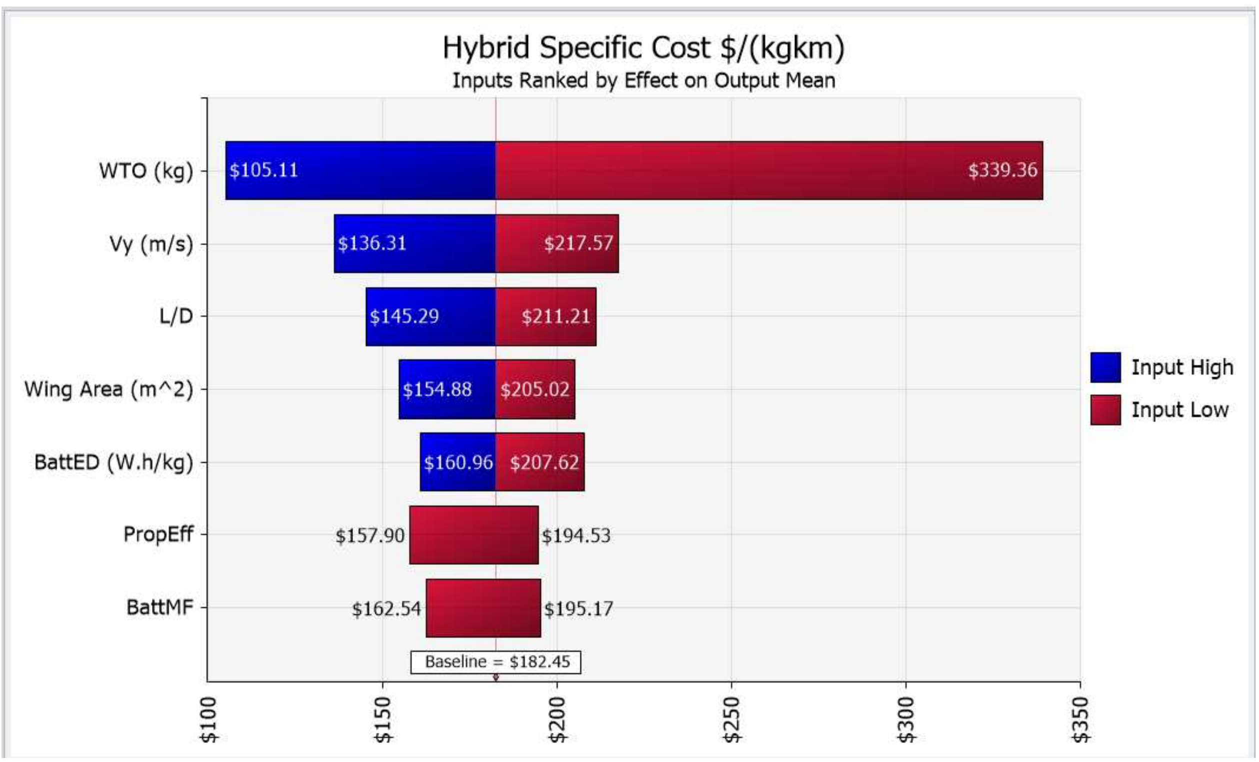

Figure 44: Tornado Chart of specific cost drivers for H-UAV (Hybrid Electric /Gas turbine)

By comparison however, vertical speed does not impact the E-UAV because after transition to efficient forward flight mode, the E-UAV is still utilizing the same energy storage density of the battery.

Potential Game Changers for Improving the H-UAV and the Systems Solution

The DSE results help us to also identify new enabling technologies for significantly improving affordability and performance. Table 12 shows that the weight of the flight controls system is 12.62 kg versus the Fuel Mass of 7.08 kg. A significant portion of the former is the weight of fan doors and flight control surface actuators. One can argue that if efficient forward flight was possible without the use of fan doors, then one could use the vectored thrust together with differential fan speed control to achieve roll, pitch, and yaw. This would have the potential for example to more than double the range or endurance of the H-UAV. Unfortunately, there is very little understanding of how a large fan-in-wing impacts the wing aerodynamic in forward flight. There are isolated references that claim that the fan-in-wing can improve the L/D of the wing (ranked number 3 in terms of impact on specific cost in Figure 44), but they are not yet applicable to predicting how the fan speed impacts the L/D versus angle of attack of the wing at different forward speeds. This would therefore be a high risk/high reward exploration.

Dropping the 4.77 kg landing gear is another significant improvement in the unlikely scenario that removing the runway take-off and landing requirement would be acceptable to stakeholders. This is also a high risk/high reward strategy where the risk is more about satisfying the stakeholder operational needs than figuring out a design that has VTOL capability without a landing gear.

Lower risk or lower hanging fruit research directions would be:

- Better packaging architecture that can increase the number of UAVs that can be transported safely to the remote launch location beyond 3.
- A matching unfolding design of the H-UAV airframe so that the operator does not have to lift any parts to get the H-UAV launch ready.
- Collaboration and communication with other repurposed autonomous airborne vehicles that can carry and deliver fire-extinguishing solutions.

A larger fleet can obviously cover a larger area of a remote forest. Human operators not required to carry heavy fuselage and wings for assembly and launch, allows the UAVs to scale up. Figures 42. 43, and 44 show that this has the highest leverage on range and specific cost of the H-UAV. Furthermore, time savings in launching, retrieval and refueling enables the driver to move the truck to a new landing/launch location to help expand the remote area that is possible to cover in one day.

The 3rd bullet above might be an answer to how we might use a H-UAV fleet to enable or repurpose existing large (autonomous) airborne assets (designed for a different purpose) to deliver a fire extinguishing payload, once the existence, location.

Therefore, in addition to new findings, this research has been a steppingstone to identify future directions for significant improvements to the H-UAV itself, in addition to enabling larger systems it can collaborate or integrate within the future.

Details of Preliminary Sizing and CAs

The sources of information for data, equations and all 18 CAs are given in Table1. The reader is also referred to the following sections of this chapter for all the details of the Monte Carlo, Optimization, Solvers and 18 CA's. Yet a few more details are included in this section, so the reader gets a rough picture of what is under the hood of DSE implementation.

Each of the 18 CAs were programmed into separate excel spreadsheets. These sheets have optimizers/solvers with linear and non-linear constraints embedded in them. The Monte-Carlo wrapper was initially written in MATLAB that generated random samples and called the spreadsheet in the loop. This worked and gave us our initial encouraging sensitivity results but were cumbersome and not easily scalable or verifiable. We then moved to @RISK add-on to Excel that allowed easy specification of statistical distributions for input parameters, collection, and generation of sensitivity charts. @Risk has a setting that enables all solvers embedded in each worksheet to be exercised for every iteration of the Monte-Carlo loop. We added several error parameters to verify that the solvers are indeed converging after the Monte-Carlo runs were completed.

The input distributions of Monte-Carlo iterations shown in Figure 35 were implemented by specifying the 1st, 50th and 99th percentile values. @RISK then computed the rest of the parameters needed for the PERT function that fitted the probability distribution function in Equation 1A.

The distribution and tornado charts above are the result of 5000 iterations of the Monte-Carlo with infeasible samples filtered out. This takes ~1.5 hours on an average engineering laptop, without using the multiple CPU option in @RISK.

Equation 1A: PDF and CDF function used in @RISK.

Density and Cumulative Distribution Functions	$f(x) = \frac{(x-\min)^{\alpha_1-1}(\max-x)^{\alpha_2-1}}{\beta(\alpha_1,\alpha_2)(\max-\min)^{\alpha_1+\alpha_2-1}}$ $F(x) = \frac{\beta_z(\alpha_1,\alpha_2)}{\beta(\alpha_1,\alpha_2)} \equiv I_z(\alpha_1,\alpha_2)$ with $z \equiv \frac{x-\min}{\max-\min}$ Here, β is the Beta Function and β_z is the Incomplete Beta Function.

There are a total of nine basic mission flight phases shown in Chapter 2 – Figure 14. However, the Climb (under electric power, phases 1 and 2) and Loiter (under gas turbine power, phase 5) are the biggest drivers for everything else, or in other words bounding. The most important output of the Climb phase is the battery size and weight required. Loiter, where the H-UAV spends most of its time) yields the fuel weight required to meet the required loiter range. The outputs of these bounding phases are used to approximate the inputs required to arrive at an optimal UAV configuration required to achieve mission requirements.[23][24][71] A summary of the most important 6 out of 18 contributing analyses (CAs) is given below.

Thrust Vectoring – Mechanical Nozzle Manipulation

The UAV architect would employ a specially designed mechanical nozzle, manipulation thrust vectoring, and wing mounted EMs (ducted fans) for the VTOL phases of flight. See

Figures 39,40 and 41 [14][15][75]. Thrust Vector Control (TVC), involves the redirection of some portion, or all the available thrust from other than the normal axial thrust axis.[75] For this application, thrust vectoring will be limited to control pitch and yaw movement about the UAV lateral and pitch axis. The wing mounted propulsor (propellers plus EMs) will control movement around the longitudinal and pitch axis. Benefits of thrust vectoring include a significant reduction in Take Off Ground Roll (TOGR), complete elimination of ground and increased maneuverability, such as is the case for aircrafts like the F35, F22 and AV8-B [75][76]. There are several TVC architectures employed on turbine ICEs. The most common architectures are rotation of the entire engine relative the aircraft; redirection of exhaust gas flow by mechanical manipulation of the ICE nozzle; insertion of movable vanes or paddles into the exhaust flow; secondary fluidic injection; diversion of the exhaust gases prior to nozzle exit. The architectures can be categorized into three basic groups: mechanical nozzle manipulation, secondary fluidic injection, and exhaust gas deflection [75]. It should be appreciated that any TVC architectures will result in a reduction of available thrust and that design considerations must account for such reductions. However, overall impact to thrust can be minimized by turning the flow in the low-speed (consider hyphen), subsonic region of head of the throat such as can be accomplished with the use of a three-bearing swivel duct (3BSD).[120] Maximum thrust loss of only 2% were observed with vector angles up to 25%.

As noted previously, the UAV propulsion architecture will employ mechanical TVC method nozzle manipulation, accomplished using a 3BSD.[120] Thrust from the UAV micro turbine ICE can be vectored from straight aft for conventional flight to straight down for VTOL operations with minimal thrust loss. For conservatism, the analysis will use 50 % of the available thrust for VTOL operations.

Climb Phase CA

The climb phase CA uses the basic momentum theory equation [8][12][19][38][64] with minor modifications to account for the behaviors of this application. The objective of this CA is to calculate the battery power required for the hover and initial climb phase of the mission.

$$(PL) = \frac{1}{V_{yc} - \frac{k_i \times V_{yc}}{2} + \frac{k_i}{2} \times \sqrt{V_{yc}^2 + \frac{2 \times (DL)}{\rho_0}} + \frac{\rho_0 \times V_{Tip}^3}{(DL)} \times \left(\frac{C_d \times \sigma_{air}}{8}\right)} \quad \text{Eq. (1)}$$

The basic input is UAV gross weight with main output being the battery power required to climb. This battery power is then used as an input to the battery CA and used with other constraints to calculate the system battery weight. Reference Table 12

Battery Sizing CA

The two fundamental UAV energy stores inputs are the fuel mass and the battery mass. The UAV battery mass is calculated by the Battery Mass CA which gets its input from the climb power CA. After getting input from the climb power CA, the battery mass CA looks at time to climb (t), Batt C rating, battery initial state of charge (Batt_SOC_i), battery final state of charge (Batt_SOC_f), battery energy density (Batt_ed), battery charge / discharge efficiency, battery package mass fraction, battery power density and calculates the battery mass based on both energy and power requirement. Reference Eq (2) and Eq

(3) The greater of the two mass (energy and power) along with the battery package mass fraction are used to calculate the UAV battery system weight. Eq (4)

Eq (2)

$$\boldsymbol{Batt_{mass_{ER}}} = \frac{\left((\boldsymbol{C_E} \times \mathbf{60}) \times \left(\frac{\mathbf{1}}{\boldsymbol{SOC_i}}\right)\right)}{\left((\boldsymbol{Batt_{ED}} \times \boldsymbol{C}) \times \left(\frac{\mathbf{1}}{\boldsymbol{e_{C\_d}}}\right) \times (\mathbf{180} \times \mathbf{0.4})\right)}$$

Eq (3)

$$\boldsymbol{Batt_{mass_{PR}}} = \left((\boldsymbol{C_p}) \times \left(\frac{\mathbf{1}}{\boldsymbol{SOC_i}}\right)\right) \Big/ \left((\boldsymbol{Batt_{EP}}) \times \left(\frac{\mathbf{1}}{\boldsymbol{e_{C\_d}}}\right)\right)$$

Eq (4)

$$\boldsymbol{Batt_{sys\_W}} = \left(\frac{\boldsymbol{MAX}\left(\boldsymbol{Batt_{mass_{PR}}}, \boldsymbol{Batt_{mass_{PR}}}\right)}{\boldsymbol{Batt_{MF}}}\right)$$

Note further that battery energy density and battery system mass fraction were explored over conventional limits to find the optimal solution for the UAV battery mass and ultimately, the UAV max takeoff weight for the desired loiter range requirement.[10][18][28][37][127]

Loiter Range CA

The Loiter Range CA uses a simplified version of the Breguet Range Equation for jet propelled aircraft, to calculate the UAV range and range fuel required ($\boldsymbol{W_0} \quad - \boldsymbol{W_1}$) for a particular gross weight configuration.[26][67][84]

$$\boldsymbol{R} = \frac{2}{c_t} \times \sqrt{\frac{2}{\rho_\infty \times S}} \times \frac{{C_L}^{1/2}}{C_D} \times (\boldsymbol{W_0}^{\frac{1}{2}} - \boldsymbol{W_1}^{\frac{1}{2}}) \quad \text{Eq. (5)}$$

Recall from the previous section that W_0 presents the weight of the UAV at the beginning of the flight segment and that W_1 is the weight of the UAV at the end of the flight segment. Hence the difference between W_0 and W_1 is the fuel consumed for the flight segment or the range fuel.

Eq. (5) can be rearranged to solve for W_1.

$$W_1 = \left(\frac{R}{\frac{2}{c_t} \sqrt{\frac{2}{\rho_\infty S}} \frac{C_L^{\frac{1}{2}}}{C_D}} - W_0^{\frac{1}{2}} \right)^2 \quad \text{Eq. (6)}$$

From Eq. (6), it becomes clear that the flight conditions for maximum range for a jet-propelled UAV are;

1. Fly at a velocity where $C_L^{1/2}/C_D$ is maximized.
2. Have a very efficiency ICE with the lowest possible thrust specific fuel consumption.
3. Fly at an altitude where ρ_∞ is small.
4. Carry as much fuel as practical.

Incremental validation is accomplished by comparing the fuel calculated using the range equation to required fuel using Eq. (7) and observing that the fuel used by a turbine ICE must be the product of the thrust required, the specific fuel consumption and the time that thrust is required by the ICE to complete the loiter phase, or

$Fuel_{loiter} = T_R \times c_t \times t_{loiter}$. Eq. (7)

As stated previously, range can be maximized or fuel requied to cover a specified range can be minimized when the UAV is flying such that the ratio $\frac{C_L^{\frac{1}{2}}}{C_D}$ is maximized.[22] Recall further that the velocity where this ratio is maximized is

$$V_{\left(C_L^{1/2}/C_D\right)_{max}} = \left(\frac{2}{\rho_\infty}\sqrt{\frac{3K}{C_{D,0}}}\frac{W}{S}\right)^{1/2} \quad \text{Eq. (8)}$$

The outputs of this CA are the range and time required to complete the loiter phase of the mission.

Results from hybrid configuration loiter range simulation indicate that the ideal weight for the UAV ~ 46.7 kg to achieve the range requirements specified. Reference Chapter 2 - Figure 17

Loiter Range Batt CA

As previously stated, the range (R) is the total distance (measured with respect to the ground) that the UAV covers on a single load of fuel or in this case, available energy for a given battery weight. The range of the UAV depends on the battery energy density, the propulsion system efficiency, the weight of the UAV and the aerodynamic efficiency. Note further that for a battery powered UAV, mass remains constant so the classical range equations can be simplified.[13][41][43][116][118]

The range is simply

$$\boldsymbol{R} = \boldsymbol{V_{loiter}} \times \boldsymbol{t_{loiter}} \quad \text{Eq (9)}$$

The time required to cover the specified range or the time until the battery energy is consumed is.

$$\boldsymbol{t_{loiter}} = \frac{\boldsymbol{m_{batt}} \times Batt_{CE}}{\boldsymbol{P_{batt}}} \text{ . Eq (10)}$$

The power required by the UAV is related to the battery power by the efficiency of the propulsion system.

$$\boldsymbol{P_{batt}} = \frac{\boldsymbol{P_{UAV}}}{\boldsymbol{n_{total}}} \text{ . Eq (11)}$$

or

$$\boldsymbol{P_{batt}} = \frac{\boldsymbol{m} \times \boldsymbol{g}}{L/\boldsymbol{D} \times \boldsymbol{n_{total}}} \times (\boldsymbol{V_{loiter}}) \quad \text{Eq (12)}$$

Combining Eq (9) and Eq (10) the expression for the battery range becomes.

$$\boldsymbol{R} = \boldsymbol{V_{loiter}} \times \frac{\boldsymbol{Batt_{sys\_W}} \times Batt_{CE}}{\boldsymbol{P_{batt}}} \text{ . Eq (13)}$$

The UAV power required can be expressed as a product of the drag and the velocity.

$$\boldsymbol{P_{UAV}} = \boldsymbol{D_{UAV}} \times \boldsymbol{V_{loiter}} = \frac{\boldsymbol{m} \times \boldsymbol{g}}{L/\boldsymbol{D}} \times (\boldsymbol{V_{loiter}}) \text{ . Eq (14)}$$

By inserting Eq (12) and Eq (14) back into Eq (13), and simplifying, the expression for the UAV battery range becomes

$$R = Batt_{CE} \times \boldsymbol{\eta_{total}} \times \frac{\boldsymbol{1}}{\boldsymbol{g}} \times \frac{\boldsymbol{L}}{\boldsymbol{D}} \times \frac{\boldsymbol{Batt_{sys\_W}}}{\text{WTO}} \text{ . Eq (15)}$$

Note that to maximize range for a battery powered UAV, the following parameters must be maximized; Fly the UAV at a velocity where lift to drag ratio is maximized, have the highest possible battery energy density, maximize battery mass fraction, and maximize the propulsion system efficiency.

During the discussion on the Monte Carlo simulation, covered later in the paper, these parameters are varied over a realistic range with a Weibull distribution, adjusted so that the most likely values are consistent with current technology maturation levels.

UAV Weight CA

The UAV multi-disciplinary analysis will involve weight, propulsion, and aerodynamic effects and how these effects influence design parameters to enable the system to satisfy a set of performance requirements. In this case, the WTO analysis follows with the identification and estimation of key contributing components of the UAV gross take-off weight (WTO) and leverages prior work completed by Valencia et al.[17] Note further that, preliminary weight estimation models have been in work for several years, due to the influence of the WTO on overall aircraft performance. The analysis leverages prior work completed by Zhang et al' [28], but also utilizes empirical data where possible, to anchor model and increase overall fidelity. For example, the primary propulsion components, the ICE, EM, and propeller weights will be directly from vendor specifications after completion of the sizing portions of the analyses.

Key components in the WTO estimations are structural ($\boldsymbol{W_{Strut}}$) and fixed equipment ($\boldsymbol{W_{FE}}$). Structural components are, the wing assembly, empennage assembly, fuselage assembly and the landing gear assembly using definitions and methods of eight estimation in references.[17][28][46][68][72][72][73][77][78]

$\mathrm{WTO} = \boldsymbol{W_{Strut}} + \boldsymbol{W_{FE}}$ Eq. (16)

Figure 45 gives a high-level overview of the process of optimizing the gross take-off weight.

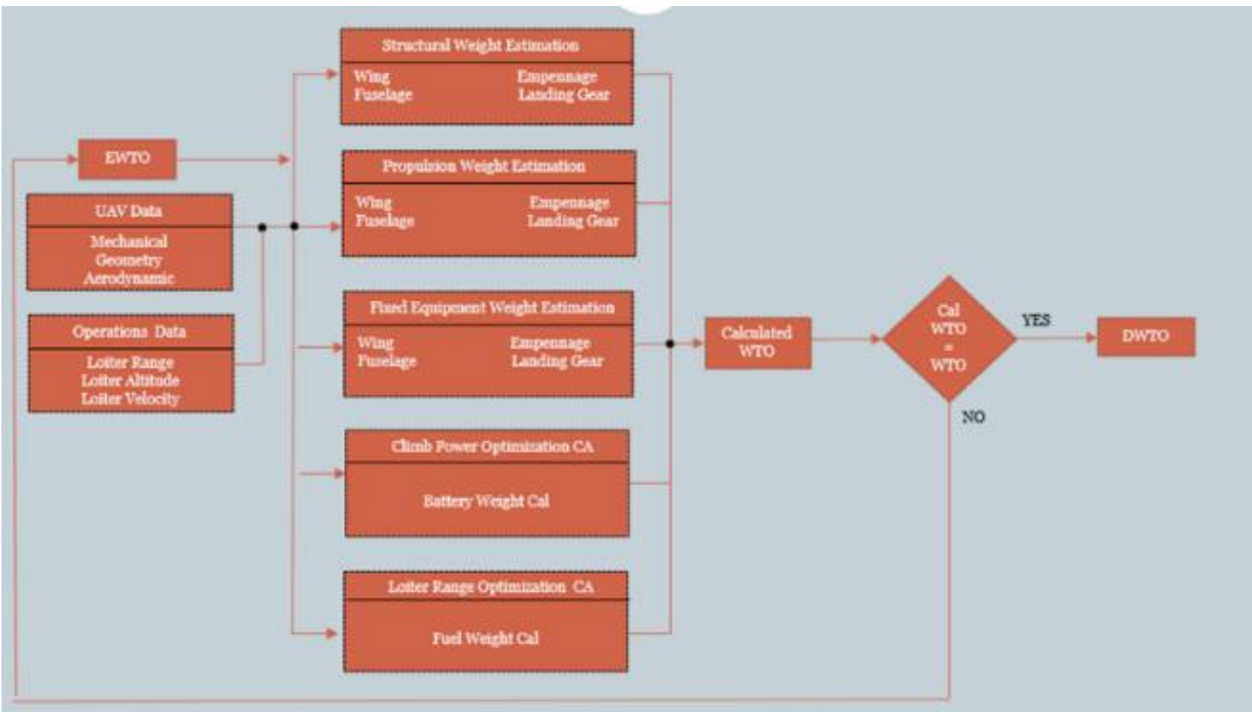

Figure 45: Optimization of take-off gross weight

UAV Cost CA

Researchers consider UAVs to be a “market discontinuity” in that the various architectures and applications are a disruptive innovation, changing the aviation industry just as telephones and personal computers did in the 1870’s and 1970’s, respectively.

[68] Sales between 2011 and 2020 are predicted to reach $61.37 B USD with 2020 sales projected to reach $7.31 B USD [76]. Researchers have also claimed that the main benefit of the UAV platform is the ability perform ISR missions with constant resolution over time or digital acuity.

These mission attributes introduce some new challenges for systems cost estimation, not previously addressed by military aircraft systems. Regardless of the target customer base, there is an obvious need for better estimation of the cost of UAV systems. Traditional software and hardware models cannot provide this need because they were created and calibrated on Human Occupied Air Vehicles (HOAV).[68][94][95]

Researchers have used several different methods to estimate the system and life cycle costs of UAVs. Among these are Expert Opinion, Bottom Up and Activity Based, Top Down and Design-to-Cost, Case Studies and Analogy and Heuristics (Rules of Thumb).

Expert Opinion is an informal approach where the cost analysis team gather opinions of experts using techniques such as Delphi or Wideband Delphi. This technique might be useful in the conceptual stages of development where there is an absence of empirical data but there are drawbacks in that there no logical ties to requirements, complexities, nor business processes.[68]

For this analysis, both the empty weight and the payload weights will be used to estimate the cost of the UAV system. An empty weight cost of $1500 per pound and a payload weight cost of $8000 per pound will be used.[68]

Verification and Validation

All the individual or basic performance (aero dynamics (lift, drag), propulsion (ICE, EM) equations that were inputs into the integrated method were semi empirical and validated at the source reference. The 1st, 50th and 99th distribution assumptions shown in Figure 35, were validated versus comparable applications in literature, supplier data sheets or interviews.

All components like EM, Fan, Gas turbine, Flight Control Actuators, Battery, Battery Management Systems, Flight Controls (computer and actuators), Landing Gear and moving nozzle are common off the shelf components so their performance, size, weight, and cost is verified in supplier data sheets and catalogues.

Furthermore, the ranking of the sensitivity of range, weight and cost to major design drivers shown in all the tornado charts are explainable via first principles, including the counterintuitive results.

The 3D CAD model of Figures 40 to 41 gave first level feedback that all major components can properly fit into the airframe and fuselage model.

We still need to verify the structural strength, aeroelastic, aerodynamic and flight dynamic requirements of the detailed design through FEA, CFD and Flight simulation.

The payload x endurance versus cost of the H-UAV compared to 8 other UAVs reported in literature provides an integrated system validation in Figure 46.

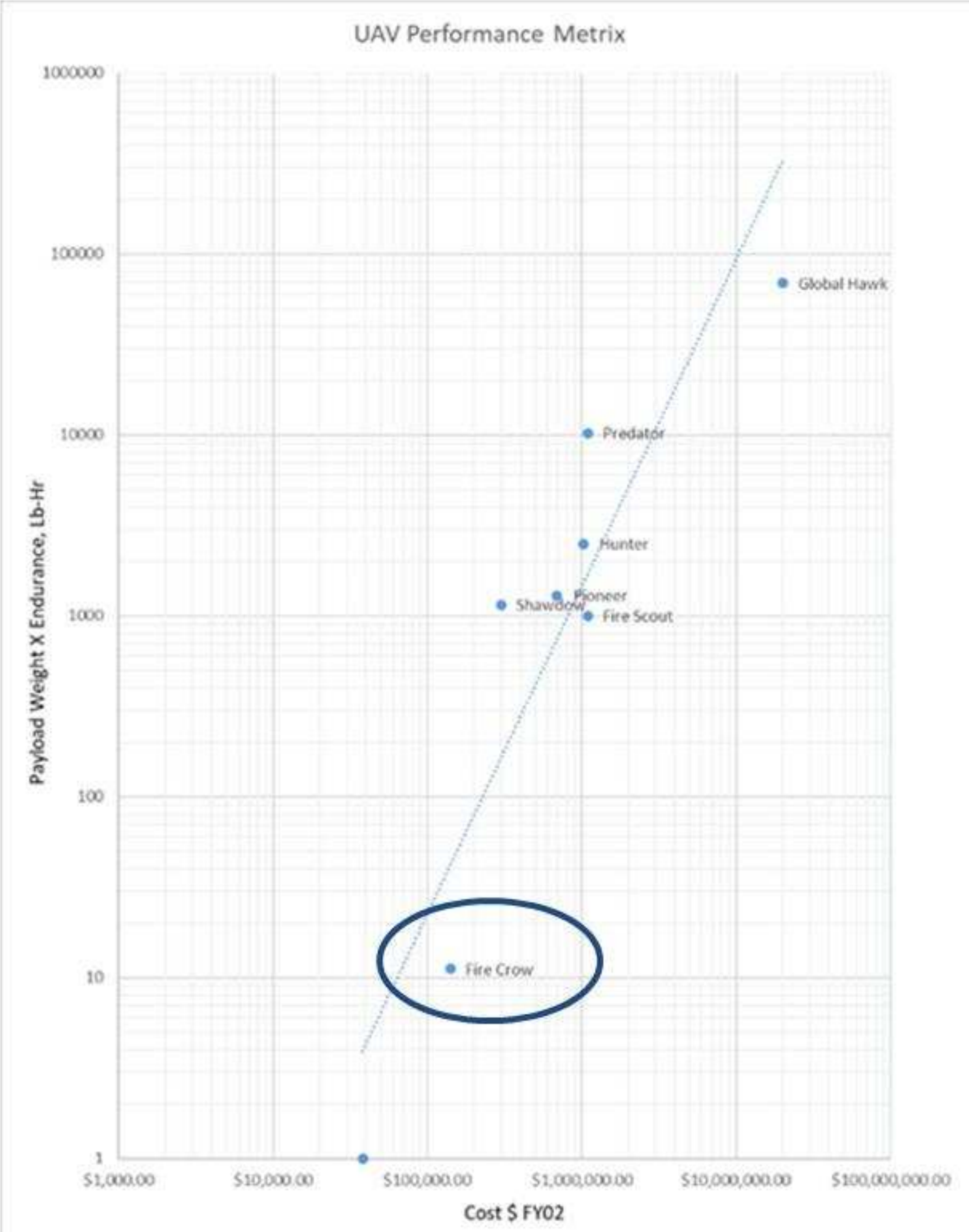

Figure 46: Comparison of H-UAV (Fire Crow) with other UAVs in literature

Major Issues and Assumptions

Severe wildfires often coincide with gusty, turbulent, or high wind conditions that pose a flight dynamic risk because they transfer energy to the H-UAV potentially causing abrupt pitch and roll responses that may lead to instability and crash, particularly during the VTOL phases of the mission close to the ground.

To reduce this risk at the conceptual sizing level, we have selected practical range of values for the Airframe, Lift Fans, Vectored Thrust and Battery that are aligned with data from existing UAVs.

However, a rigorous way to mitigate this risk is to include it in a detailed flight control trade-study to find the best flight controls architecture followed by dynamic simulation and test to verify that the H-UAV can manage the adverse flying conditions safely. This is a topic of parallel research work kicked-off at CSU System Engineering department. This research is also intended to evaluate the validity of the following assumptions:

- The EM/Fan and Vectored thrust from the Gas turbine are both sized to provide 60% of the total lift required during the climb to hover and transition to wing borne segments of the flight.
- Battery discharge/recharge rate is higher than the worst-case total demand for VTOL, GN&C computer, flight control actuation and integrated sensor package, in all flight phases.
- Total power and energy stores required is the sum of the energy required from each phase Etot (Battery + Fuel) = 2 X (E_{hover} + E_{climb} + E_{dash}) + E_{loiter}.

- Total power electric power offtake from the gas turbine during phase 4, 5 & 6 (Dash, Loiter, Dash) shall not exceed 2 to 5% of total gas turbine power and this power off take shall be sufficient to charge up the battery to 100% prior to landing.
- The EMs for driving lift fans are "brushless" permanent magnet synchronous type – see *AIAA class presentation 22 July 2020.*
- Operating volts ~ 270 volts.
- The Micro gas turbine is a PBS TJ80, has a thrust specific fuel consumption (TSFC) = 1.137 lb./lbf/hr or 3.4 X 10^-4 N/N. s.[83]
- The gas turbine drives an electric generator that drives the lift fans (i.e., no direct mechanical coupling).
- RoC at service ceiling is V_{yc} = 0.5 m/s for subsonic aircraft from.[22][67][68]
- No wing area under lift fans eliminates the concern for down wash counter acting the thrust / power required to hover and climb.[119]
- Assume simple wing design with electrically actuated trailing edges to provide flaps and aileron functions. C_{Lmax} range is 1 to 2.4.[6][9][22][82]

Observations for the H-UAV

Max range is achieved by flying at a loiter velocity where maximum drag polar is achieved and not maximum L/D when constrained by feasible lift coefficient values. Any weight savings through new technology or architectural changes or design optimization can translate to extra range, endurance, and lower specific cost.

As mentioned earlier, a game changer might come from the flight controls system by dropping the classical control surfaces, actuators, and fan doors. However not enough is known about the aerodynamics of Fan-in-Wing to answer this critical but basic question: Would running the fan-in-wing at low speed in forward flight break even with the fixed wing L/D at a low percentage of power-off take (say 2% to 5%) from the gas turbine? If so, then the battery will stay charged during forward flight while the weight savings (due to dropping classical controls) shall lead to factors improvement in range, endurance, and specific Cost.

Will higher energy density battery help the H-UAV cost and survey time? Figures 28,35,37 show that battery energy density has measurable impact, but it is not a big hit on either.

Note that the any improvement in battery energy density technology shall not come at a cost to max allowable charge and discharge rates. Otherwise, the weight saving will be offset by the need to oversize the batteries to manage the rapid charge/discharge requirement.

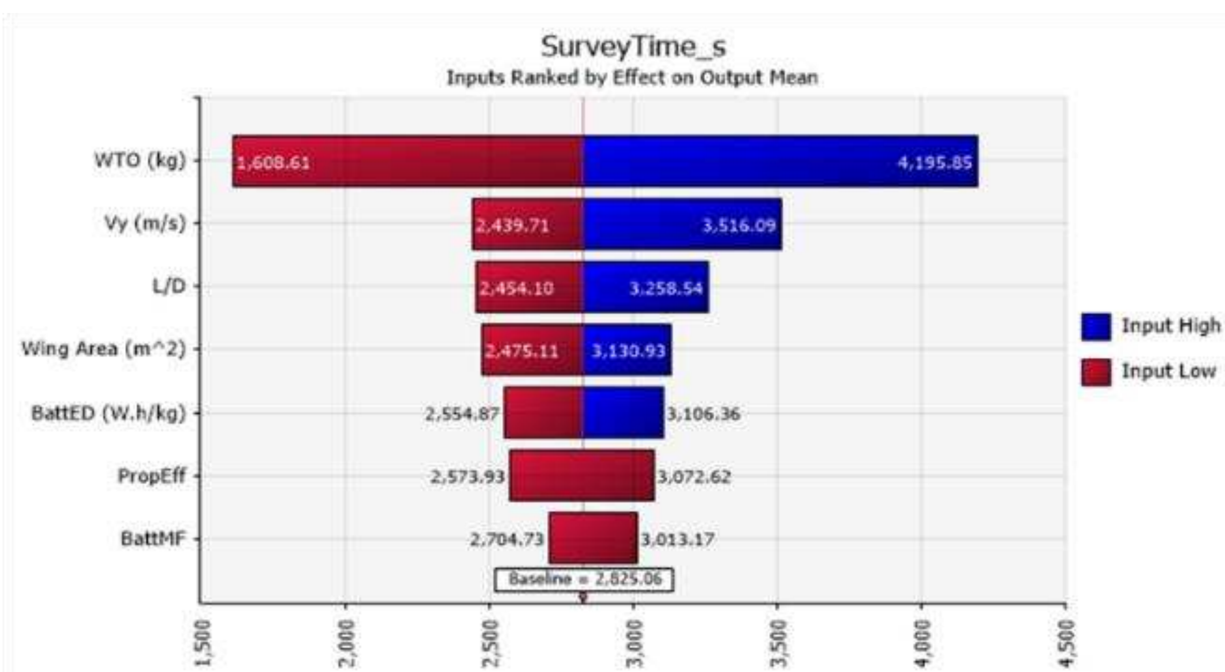

Figure 47: Tornado Chart of Survey Time for the H-UAV

Fuel cells may have higher effective system energy densities as compared to a Lithium or Sodium battery but cost and availability of an efficient unit for this small size are still major challenges whereas battery packs are readily available and can be more easily packaged into the available space in the fuselage.[2][5][29][30][40][44][45][47][49][51][53][54][56][57]

When will the E-UAV Shine?

Specific energy density for a battery system is ~ 32 times less than for heavy fuels [3][4][50][52]. When energy conversion efficiencies are account for, that number can be reduced to ~ 12 times.

Figure 47 shows that we can practically expect a maximum improvement of 42 km (due to Battery Energy Density) and 21 km (due to Battery Mass Fraction, a measure of battery system overhead) improvement in the range of E-UAV that with current technology has a baseline range of 83 km. Hence the best-case range for the E-UAV due to battery technology improvements is 146 km which is comparable with baseline (not best case) technology H-UAV at 147 km from Figure 47.

Assuming predictions for future practical battery energy density and mass fractions (shown in Figure 48) hold, then it will be possible for the E-UAV to meet the wildfire detection requirements. However, based on the H-UAV results we cannot claim that we have found a way for the E-UAV to shine versus H-UAV in terms of cost, weight, and range.

Note that the H-UAV and the E-UAV have a similar architecture in this study. It may be possible for the E-UAV to shine if its architecture is drastically different, such as distributed points of electrically driven propulsion along the wing etc.

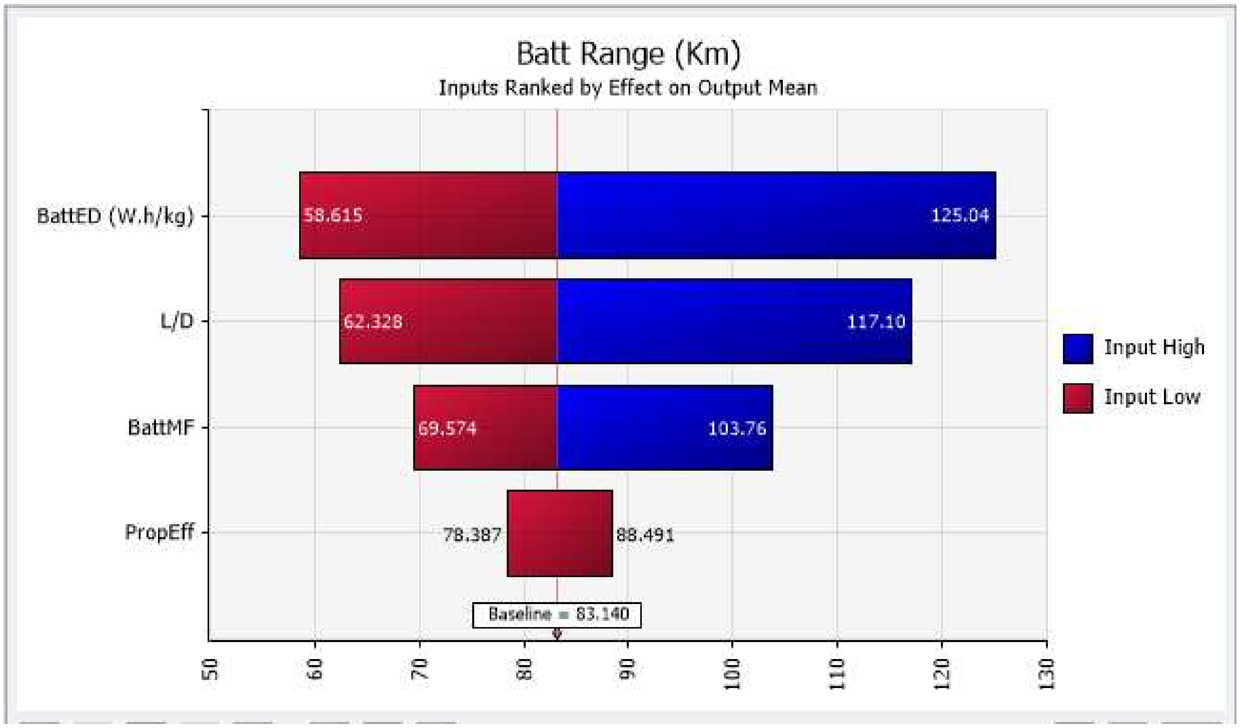

Figure 48: Tornado Chart for Range of E-UAV

The E-UAV versus H-UAV conclusions may be impacted when we add safety and environment considerations to cost, weight and range. For example, our study does not yet include a crash scenario to see if the E-UAV has a significant relative benefit in terms of not causing fires in a crash.

Wind Effects

UAVs can be more suspectable to wind effects due to several factors including takeoff weight, wing loading, operational altitude, relative velocity, and method of propulsion. Wind effect can be viewed simply as energy transfer where the wind energy is transferred to the UAV causing a change of energy state of the UAV which in turn can result in a change in flight attitude and in some instances, a crash particularly when the wind effects occur close to the ground.[96] There has been a couple of high-profile instances UAV crashes because of wind effects; the Google Solara 50 due to hot updraft while operating close to the ground and the Facebook Aquila structural failure because of strong wind gust. Researchers have agreed that to reduce the UAV mission operations risk, consideration must be made in the UAV architecture and simulations conducted on executable models / digital twins.

Wind effect will be covered by the Design Exploration Research. DSE research activity explored a viable range of input parameters – L/D, Drag Polar, Propulsion efficiency, gross takeoff weight, battery energy density, battery mass fraction etc., all of which capture considerations for the effect of wind.

Design Space Exploration Conclusion

An earlier reported trade study [7] found that a small fleet of VTOL H-UAVs, transported to the edge of the forest on the back of a mid-size truck, would likely beat other land-, air- and space-based architectures developed for the purpose of detection and communication of wildfires. In this paper, we report the next step: a coupled architecture / executable model formed by the integration of MBSAP with Design Space Exploration. This helped us find the optimal design size, weight, cost, and performance of the H-UAV, in addition to the sensitivity of range, weight and cost to major design drivers and technology measures.

Given that the severity and adverse impact of wildfires is growing in the US and the World, the good news is that this work has identified a feasible low-cost, locally owned, and operated VTOL H-UAV concept (shown in Figures 40 to 41) that meets stakeholder needs and operational requirements, using only current levels of technology and off the shelf components such as battery, lift fans, gas turbine, ducting, fuel tank and nozzle etc.

The Monte-Carlo sensitivity results also identified at least four realistic directions for improving the specific cost well beyond the 182 \$/(kg.km) of the current technology baseline H-UAV. These directions are scaling up the gross take-off weight, increasing climb velocity, increasing L/D and Wing Area in ranked order.

This work also showed that an E-UAV of a similar architecture would in principle become feasible, if the expert estimates on best future practical battery energy density and battery mass fraction are realized in practice. We have not yet found a scenario or architecture where the E-UAV shines relative to the H-UAV.

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Chapter 5

Risk Study

Introduction

The risk management process is fundamental to effective Systems Engineering (SE), at all levels and usually includes risk identification, analysis, prioritization, planning and monitoring. MBSE and this architecture centric method formalizes SE using models to reduce both technical and programmatic risk. While the earlier chapters were more focused on methodologies to reduce technical risk, this Chapter presents a process pattern which can be used to reduce programmatic risks during the next stages of UAV development.[60]

Risk Process Description

A risk is a time bound event with some probability of occurrence which will have impact to the project. *See "Proactive Risk Management by Preston G. Smith & Guy M. Merritt".* [91][92] The impact can affect the principal indices of the project such as cost, schedule or technical as well as resources, stakeholder level of interest, new laws, environment etc.

For this discussion, the focus will be on the standard risk model where the risk, impact and total loss are identified and, the risk and impact are separated so that drivers for each can be identified.

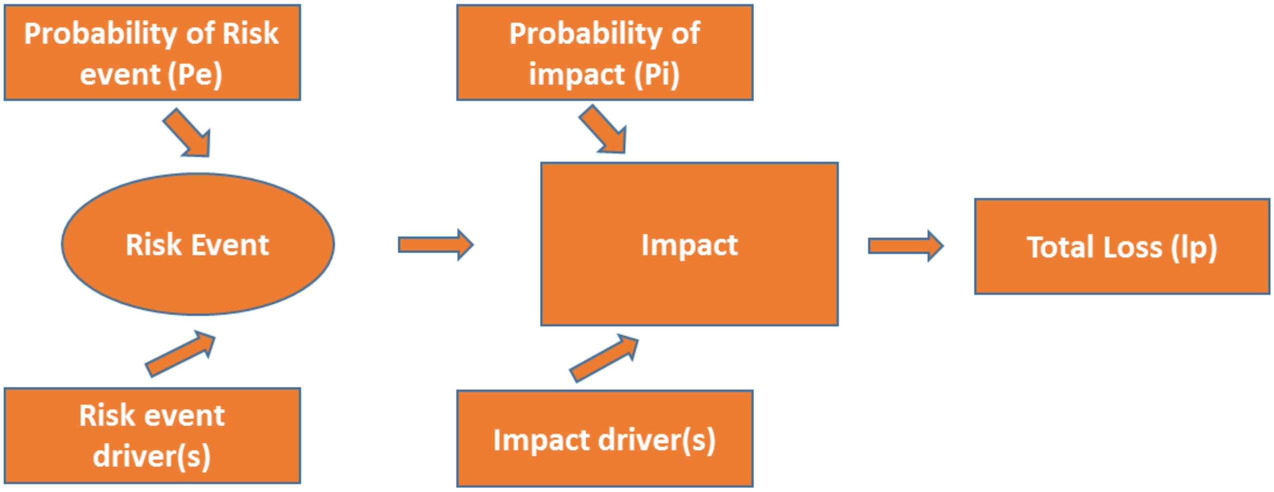

Figure 49: Risk Process

There are five distinct risk management steps in the process; risk identification, risk analysis, risk prioritization, risk planning and finally risk monitoring.

The first step, risk identification is accomplished by facilitating an event which is attended by a cross section of the entire project team including stakeholders. Project risks are identified along with the consequences which could prevent the project from satisfying the intended goals. Risk identification is accomplished at the beginning stages of a project and is intended to be free form brainstorming without must judgement. There are four basis categories of risks: technical, external, organizational, and management.

Facilitation is an important aspect in the risk process and must be conducted by a skilled practitioner, who is also well versed in the risk management process.

There several different methods used to capture risks; Brainstorming, Delphi technique, Interviewing and Root Cause Analysis

Brainstorming: This method of risk identification involves the use of experts who may or may not be part of the project team, in a session lead by a facilitator to capture project risk without applying any judgements.

Delphi technique: This method is used to reach a consensus of experts under the condition of anonymity. The facilitator submits a questionnaire about project risks then collect the responses, affinitize then resubmits for further input. Consensus is reached after a few cycles.

Root cause analysis: This is an investigative approach where technique such as Reality Charting or Fish Bone analysis is used to analyze the problem, discover root causes, and develop action plan to prevent recurrence of the issue. In the case of Reality Charting, an action and a condition cause are identified for each branch of the chart. Action plans are adopted to address the conditional causes to prevent recurrences.

Interviewing: This method is as implied, simply conducting interviews session with subject matter experts and stakeholders to identified project risks.

The second step is risk analysis which is first qualitative and finally quantitative. Qualitative in that the key stakeholders may decide to actively manage a risk that falls below the threshold value established. The pivotal point in this step is the development of expected loss for each risk identified. This is important because these relative values are used in the next step to establish which risks the team will work on. A probability is assigned to each risk and impact, the product of which is then multiplied by the total loss to arrive at an expect loss. The numeric value is then used to establish the order of importance of each identified risk.

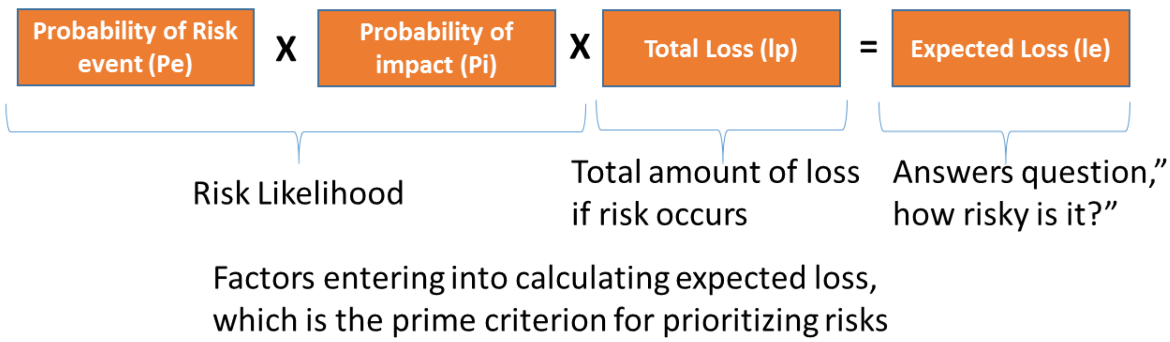

Figure 50: Risk Quantification [94]

The third step is risk prioritization and will involve the same team and the creation of an ordered list of importance defined for the identified risks. It is important that the risk manager review the results with key stakeholders so the adjustment could be may to the probabilities if a result is counter intuitive.

Following with the quantitative sub-step, a risk map is created, and the risk likelihood values are plotted with the likelihood on the Y axis and total loss on the X axis. The threshold values are also plotted, and a trend line applied. Risks falling above the threshold value trend line are tagged for Active risk management while the other risk will be accepted and revisited as the project work is completed. There needs to be a balance between the resources working risk management and resources working other core activities for the project so to that end, the risk manager with agreement from other key stakeholders, including management, may decide to remove or add risks from/to, the active management list which were previously identified.

The fourth step is risk planning. There are several strategies to manage risks – four basis approaches are avoided, transfer, mitigate and accept. The discussion will focus on mitigation plans. To mitigate risks, the risk manager work to identify the risk and impact drivers and formulates plans to work on the drivers so that the risk is eliminated or the probability of the risk and or the impact is reduced. Contingency, in the form of schedule margin or budget is also developed during this step.

During the fifth and last step, risk monitoring, the risk manager or project manager routinely assess progress to date on the risk mitigation plans developed in step fourth. One of the pitfalls that project team fall into is not working the risk mitigation plans after investing the time to develop these plans. There may be opportunities to retire some risks because the action plans for the drivers were completed or the time frame for the risk event has transpired. The risk manager may also reexamine inactive risks and elevate to active status if necessary.

Risk Identification – Step 1

The objective of this process is to identify which risks will affect the project and to define the consequences, and time frame for each. **Plan and Prepare**

Risk planning should be accomplished at the beginning stages of a project alone with scope, schedule, and budget development. In fact, during the risk identification process, risks maybe identified that may lead the major stakeholders to change the scope of the project or forego the project entirely.

To identify all relevant risks, it is important that the team understand the full scope of the project. The project manager or preferably an independent facilitator should present a very thorough project overview. At this point, there needs to be commitment from that team members will participate and that there is good representation of all functions of the project including customer and major stakeholders. The team assembled had a good balance of risk tolerant individuals to avoid unnecessary expense and conservatism.

There should be an agreement on which risk model will be utilized. In our case, we will use the standard risk model.

Of the many techniques available to identify risks for this project, expert judgement, brainstorming, and interviewing were used to identify the nine project risks listed in Table 13.

Several subject matter experts in the aerospace industry and fire-fighting industry were interviewed, to identify the risks listed in table 1. Note that 9 risks were identified and are already prioritized / sorted.

Table 13: UAV Risks

Risk ID	Risk Event	Risk Impact
140	The Sensor Specialist will not be available	there is a limited number of resources
105	Project Funding will not be available or may not match the project schedule	Not able to integrate payload compliment
115	The CO / CA Fire Resource will not be available	missed critical needs / incomplete objectives
125	There maybe a FAA regulation change - max operational altitude	max operational altitude for commercial UAV operations 400 ft AGL
101	Lab facilities in either CO or CA will not be Available	Not able to complete proof of Concept
110	Mechanical Resource will not be availabile for critical integration activities	late integration
130	The location chosen for flight testing will not be availabe	location may restrict flight testing
120	There maybe an FAA regulation change - max weight of UAV	additional development cost
135	The FAA - DAR will not be available	FAA representatives may not be available for initial inspection of the platform

Facilitating the Session

Facilitation sets the foundation on how the team will perform proactive risk management and as such, it is especially important that the project manager secures the services of a skilled facilitator. The team must include representatives from all the functions involved in the project including key stakeholders like customer representatives. A good strategy is to include individuals with different backgrounds not related to engineering to offer alternative perspectives on project issues and to mitigate the effect of *group think*.

The facilitator should also conduct some form of training in the risk process to bring the team up to a fundamental level of understand of proactive risk management and maybe reenforce the importance of this process as well. It is important that this process start early but not too early. For the development of the wildfire detection and communication platforms, the risk process was initiated during the concept exploration phases and is continuing into the concept definition phase. There are some negatives in that there may be risks identified for concepts that will not be taken into advanced development and detail design. This was a worthwhile process step because, the risks identified were part of the trades and decision process to converge on the leading concept. In this case, the team has decided to focus on the UAV concept. The standard risk model with drivers and impact, expected loss are all related to this concept. As other concepts are developed during the completion of the concept exploration phase, initial risk management will also be applied to those concepts.

Risk Analysis – Step 2
Establish the Facts

The pivotal point of this step is the uncovering of why an expert team member believes that the risk event and or the impact will occur. It is also important that the facilitator uncovers the facts on any historical performances which can form the basis for developing probabilities for the drivers. As mentioned above, it is important that three to five driver facts be developed for each risk and impact event.

For the UAV concept, the needs analysis is only partially completed so there is a risk that the team will not capture all requirements and as such system requirements and functional requirements maybe de missed as the team moves into concept definition, advance development, and detail engineering design. Reference list of drivers in the table above.

Developing Risk Event Drivers

During this step, the facilitator attempts to uncover why the originator of the risk believes that the event will occur and captures these drivers on a spread sheet tool. A technique utilized by General Patton to condition his commanders to also have substantiated statements, was to ask, "how do you know this". This technique was utilized to develop the risk and impact drivers for all 9 project risks. As an example, reference risk 125 "FAA regulation changes" where there have been recent regulation changes governing what altitudes that commercial UAVs can fly to avoid interference with crewed aircrafts. Also offered up as confirmation of the risk was a reference to a *Washington Post* article where it was reported that there were at least 25 episodes in which UAVs came within a few seconds of Collison with crewed aircrafts.

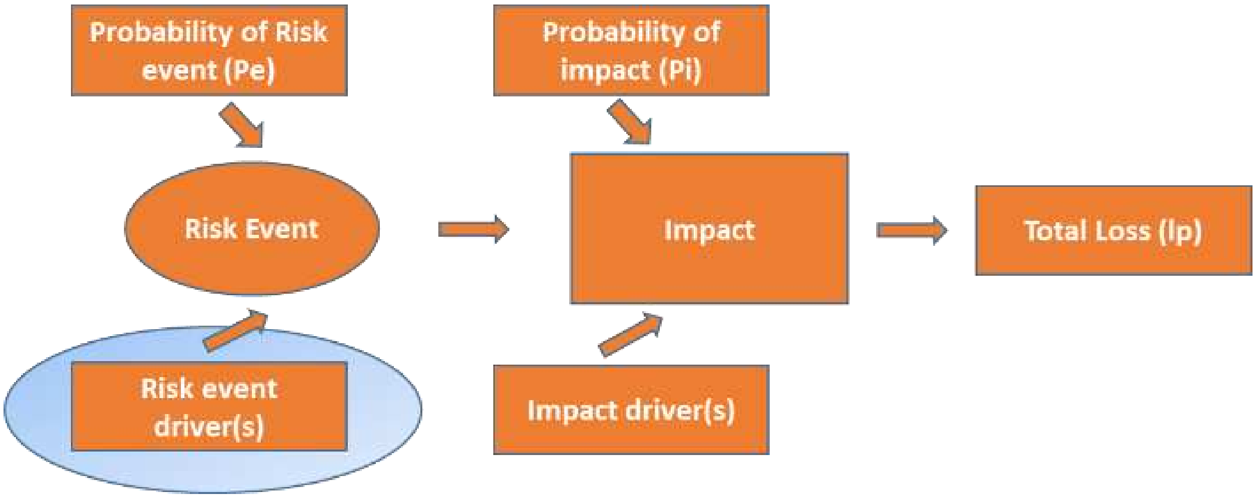

Figure 51: Risk Process – Event [94]

Developing Impact Drivers

Impact drivers are developed in the same manner as risk event drivers and in addition answers two central questions – what is the likelihood that the impact will occur and what facts would be used to show the magnitude of the total loss.

Three to five drivers were identified for each of the nine project risks and impacts. It is important that a sizable number of drivers be identified so that the project team have good options for implementation plans to either eliminate the risk or mitigate the impact.

It is important to re-establish that the occurrence of a risk event does not mean that the consequence of the impact will be realized. See the table above for a list of impact drivers. Also reference the figure before.

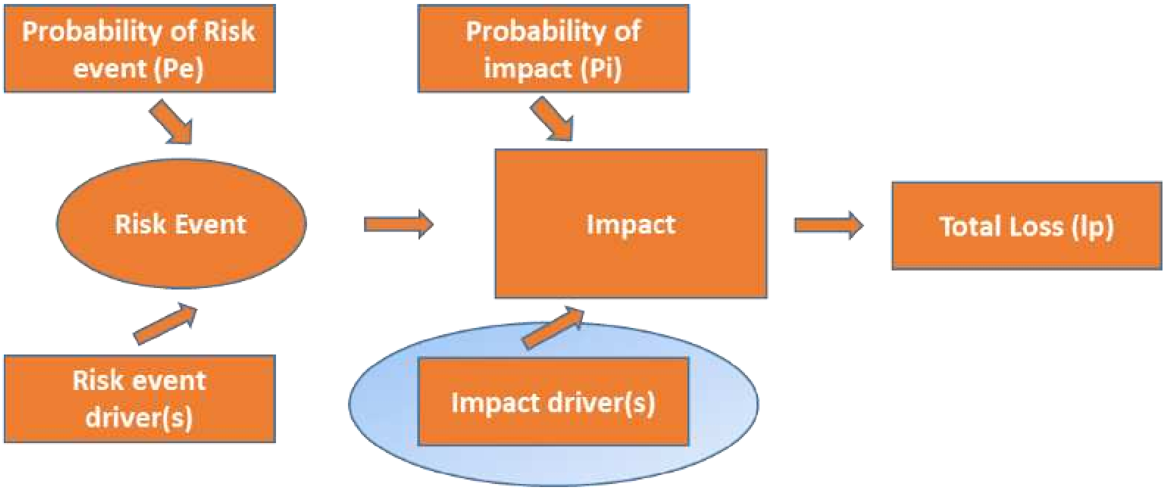

Figure 52: Risk Process Impact Drivers [94]

Quantifying Total Loss

It is preferable that the total loss be defined in more tangible units such as time of money. Other units can be used and will depend on the organizational preferences. Whatever is decided, consistency is important. It is preferable that impact drivers be developed with consistent units so that prioritization is more straight-forward. However, if mixed units cannot be avoided, a calibration table should be used as an aid in prioritization. The facilitator should pay particular attention to the length of time needed to develop the total loss. Too much time is a sign that driver statement was not properly developed. See table 3 for the total loss for the UAV project. These quantities were developed from a review of costs of similar platforms and expert knowledge.

Table 14: Quantify Total Loss

Risk ID	Risk Event	Risk Impact	Risk Probability ' post AP	Risk Probability	Impact Probability ' Post AP	Impact probability	New Risk Liklihood	Risk Liklihood	Total Loss	Expected Loss Post AP	Expected Loss	Risk Theshold	Risk Priority	Status
140	The Sensor Specialist will not be available	there is a limited number of resources	0.3	0.6	0.65	0.7	0.195	0.42	$ 10,000.00	$ 1,950.00	$4,200.00	0.20	1	Active
105	Project Funding will not be available or may not match the project schedule	Not able to integrate payload compliment	0.13	0.26	0.67	0.78	0.0871	0.20	$ 20,000.00	$ 1,742.00	$4,056.00	0.10	2	Active
115	The CO / CA Fire Resource will not be available	missed critical needs / incomplete objectives	0.2	0.4	0.5	0.6	0.1	0.24	$ 12,000.00	$ 1,200.00	$2,880.00	0.17	3	Active
125	There maybe a FAA regulation change - max operational altitude	max operational altitude for commercial UAV operations 400 ft AGL	0.25	0.5	0.3	0.7	0.075	0.35	$ 6,000.00	$ 450.00	$2,100.00	0.33	4	Active
101	Lab facilities in either CO or CA will not be Available	Not able to complete proof of Concept	0.15	0.45	0.6	0.7	0.09	0.32	$ 5,500.00	$ 495.00	$1,732.50	0.36	5	Inactive
110	Mechanical Resource will not be availabile for critical integration activities	late integration	0.12	0.23	0.45	0.5	0.054	0.12	$ 4,500.00	$ 243.00	$ 517.50	0.44	6	Inactive
130	The location chosen for flight testing will not be availabe	location may restrict flight testing	0.2	0.4	0.3	0.4	0.06	0.16	$ 4,000.00	$ 240.00	$ 640.00	0.50	7	Inactive
120	There maybe an FAA regulation change - max weight of UAV	additional development cost	0.15	0.3	0.13	0.15	0.0195	0.05	$ 5,000.00	$ 97.50	$ 225.00	0.40	8	Inactive
135	The FAA - DAR will not be available	FAA representatives may not be available for initial inspection of the platform	0.1	0.2	0.15	0.3	0.015	0.06	$ 3,000.00	$ 45.00	$ 180.00	0.67	9	Inactive

Probability Estimation Techniques

Several different techniques can be used to arrive at the probability for a risk event and its impact, the product of which will be the likelihood of the impact if the risk event occurs. Techniques such as group consensus, individual assignments and wide band Delphi are particularly effective when used by the skilled facilitator, in developing risk and impact probabilities. Probability estimates are not based on the risks but the drivers of the risks and impacts. Guideline presented on page 75 of Proactive Risk Management, were used to develop the probabilities for the UAV drivers. See Table 14 above.[94] As an example, in developing the probability for risk 140, the engineering and management team agreed that since there were only 5 known sensor experts, that it would be difficult to secure expert services for critical interface definitions. Further, the team felt that the chance of occurrence was equal to or greater than 40.5 but less than 60.5 percent (not much less) so 60 percent rather than 50 percent was used. Likewise for risk 105, the probability of occurrence was equal to or greater than 20.5 percent but less than 40.5 percent, so the team settled on 26 percent as appose to the 30 percent recommended in the text. The percentage (26 percent) was justified because the project manager felt that there was an ability for more positive control of the risk drivers.

Calculate Expected Loss

Expected loss is the product of the likelihood and the total loss. It is important to note that this is a relative quantity used in later step to prioritize the risks. See Figure 53 and Table 15 below.

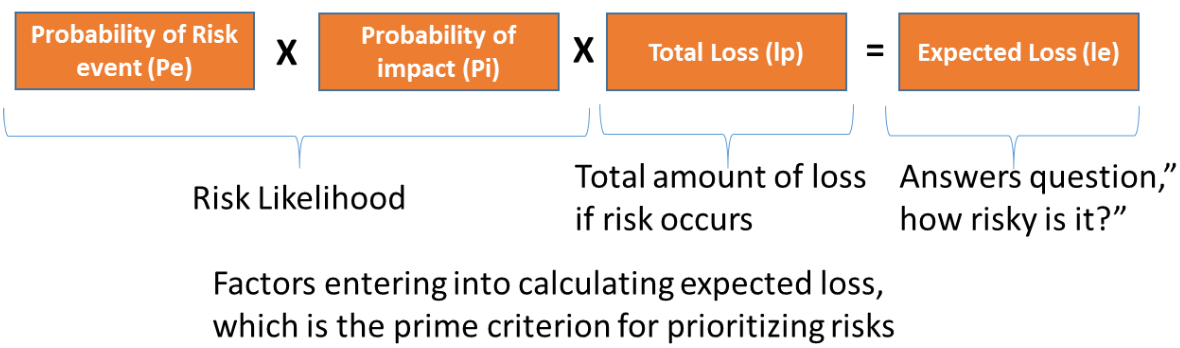

Figure 53: Expected Loss

Table 15: Expected Loss Approximation

Risk ID	Risk Event	Risk Impact	post AP	Probability	Post AP	probability	Liklihood	Liklihood	Total Loss	Post AP	Loss	Theshold	Priority	Status
140	The Sensor Specialist will not be available	there is a limited number of resources	0.3	0.6	0.65	0.7	0.195	0.42	$ 10,000.00	$ 1,950.00	$4,200.00	0.20	1	Active
105	Project Funding will not be available or may not match the project schedule	Not able to integrate payload compliment	0.13	0.26	0.67	0.78	0.0871	0.20	$ 20,000.00	$ 1,742.00	$4,056.00	0.10	2	Active
115	The CO / CA Fire Resource will not be available	missed critical needs / incomplete objectives	0.2	0.4	0.5	0.6	0.1	0.24	$ 12,000.00	$ 1,200.00	$2,880.00	0.17	3	Active
125	There maybe a FAA regulation change - max operational altitude	max operational altitude for commercial UAV operations 400 ft AGL	0.25	0.5	0.3	0.7	0.075	0.35	$ 6,000.00	$ 450.00	$2,100.00	0.33	4	Active
101	Lab facilities in either CO or CA will not be Available	Not able to complete proof of Concept	0.15	0.45	0.6	0.7	0.09	0.32	$ 5,500.00	$ 495.00	$1,732.50	0.36	5	Inactive
110	Mechanical Resource will not be availabile for critical integration activities	late integration	0.12	0.23	0.45	0.5	0.054	0.12	$ 4,500.00	$ 243.00	$ 517.50	0.44	6	Inactive
130	The location chosen for flight testing will not be availabe	location may restrict flight testing	0.2	0.4	0.3	0.4	0.06	0.16	$ 4,000.00	$ 240.00	$ 640.00	0.50	7	Inactive
120	There maybe an FAA regulation change - max weight of UAV	additional development cost	0.15	0.3	0.13	0.15	0.0195	0.05	$ 5,000.00	$ 97.50	$ 225.00	0.40	8	Inactive
135	The FAA - DAR will not be available	FAA representatives may not be available for initial inspection of the platform	0.1	0.2	0.15	0.3	0.015	0.06	$ 3,000.00	$ 45.00	$ 180.00	0.67	9	Inactive

Prioritize and Map Risks – Step 3
Sort Risk by Expected Loss

To start the prioritization process, expected loss for each of the identified risks are calculated (Figure 53) and sorted – See Table 16 below. For the UAV development project, total loss and by extension expected loss is expressed financially. Other project measure like schedule or other maybe used. To simplify comparison and sorting, it is important that the risks total and expected loss have the same measure of quantification.

Develop a Risk Map

Note that Table 16 is sorted by values in the expected loss column. Also, a status column was added, and formula applied “=IF(H3>2000,”Active”,”Inactive”)” to set value as either active or inactive. The threshold value was set to $2000 so that the project manager could capture and actively manage the risks that were thought to be critical to the research project (risk 105, risk 115, risk 125 and risk 140).

On reexamination, perhaps it would have been better to set the threshold at 10% of the project value which is estimated to be around $60K (threshold would have been about $6K).

Finally, the intention is to use the threshold value as a guideline to establish which risks to actively manage, but it is up to the team to decide which risks to actively manage based on perceived importance to the project. As an example, the team may decide to actively manage risk 101 although it is currently below the threshold, because of the importance of having the right integration facility available.

See chart below – risk map with the threshold line and the risk of interest shown above the threshold line.

Table 16: Risk Thresholds

Risk ID	Total Loss	Risk Liklihood	Risk Theshold
105	$ 20,000.00	0.20	0.10
115	$ 12,000.00	0.24	0.17
140	$ 10,000.00	0.42	0.20
125	$ 6,000.00	0.35	0.33
101	$ 5,500.00	0.32	0.36
120	$ 5,000.00	0.05	0.40
110	$ 4,500.00	0.12	0.44
130	$ 4,000.00	0.16	0.50
135	$ 3,000.00	0.06	0.67

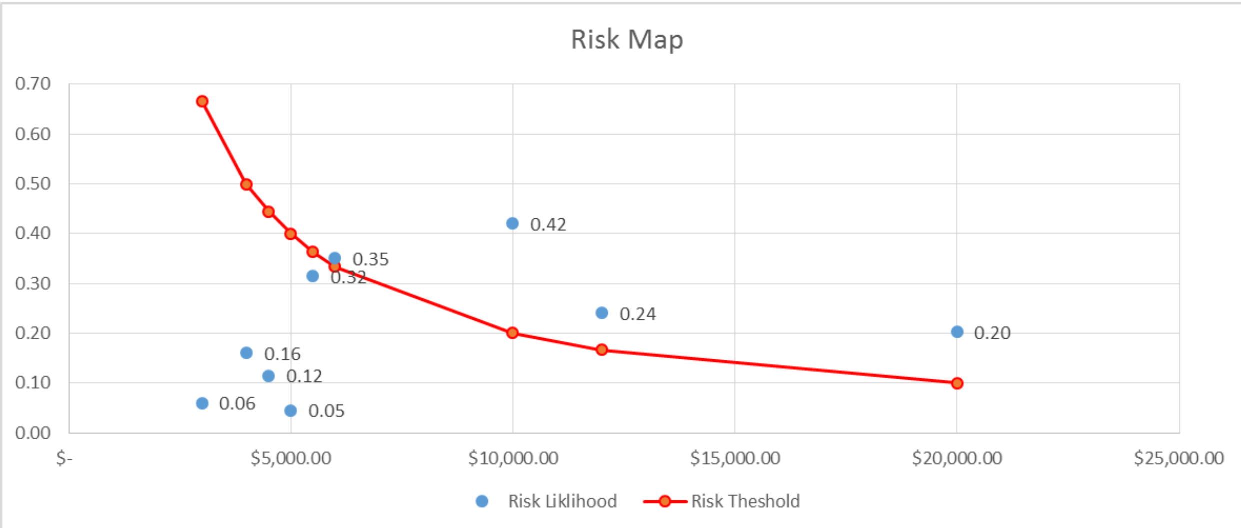

Figure 54: UAV Risk Map

Risk likelihood is the y axis and Total loss is on the X axis.

Note that the solid line on the graph is constant expected loss and separates the risks that will be actively managed by the team from those that are inactive. The four risks to the right and above the line are risk 140, 125,105 and 115 with risk likelihood values of 0.42, 0.35, 0.20 and 0.24, respectively.

As we move forward with the risk management process, the concern is that we manage the correct number of risks so as not to be surprised later in the project with unanticipated issues. This need must balance against the budget requirements needed to manage many risks – a very conservative approach.

Develop a Prioritized List

The prioritize list was developed using the expected values and applied a simple formula to set the status column to active or inactive – see Table 16 above and Table 17 below. The risk identified as active will be managed by the team going forward.

Table 17: Risk Summary

Risk ID	Risk Event	Risk Impact	Risk Probability ' post AP	Risk Probability	Impact Probability ' Post AP	Impact probability	New Risk Liklihood	Risk Liklihood	Total Loss	Expected Loss Post AP	Expected Loss	Risk Theshold	Risk Priority	Status	Risk Strategy
140	The Sensor Specialist will not be available	there is a limited number of resources	0.3	0.6	0.65	0.7	0.195	0.42	$ 10,000.00	$ 1,950.00	$ 4,200.00	0.20	1	Active	Mitigation
105	Project Funding will not be available or may not match the project schedule	Not able to integrate payload compliment	0.13	0.26	0.67	0.78	0.0871	0.20	$ 20,000.00	$ 1,742.00	$ 4,056.00	0.10	2	Active	Mitigation
115	The CO / CA Fire Resource will not be available	missed critical needs / incomplete objectives	0.2	0.4	0.5	0.6	0.1	0.24	$ 10,000.00	$ 1,000.00	$ 2,400.00	0.20	3	Active	Mitigation
125	There maybe a FAA regulation change - max operational altitude	max operational altitude for commercial UAV operations 400 ft AGL	0.25	0.5	0.3	0.7	0.075	0.35	$ 6,000.00	$ 450.00	$ 2,100.00	0.33	4	Active	Mitigation
							Totals		**$ 46,000.00**		**$ 12,756.00**				

Communicate the Prioritized List

The team maybe concerned that there are risks that will not be actively managed by the team. The project manager should schedule another risk review and communicate to the team how the probabilities were estimated, how the likelihood was calculated, how the expected loss was calculated, how the threshold value / curve was set and finally how the risks were identified and active and inactive. For the UAV project example, $1500 expected value was established as the threshold value because risk above this value was considered important to the project.

Resolve Risks – Step 4
Risk Resolution Process

The goal of this part of the process is to develop action plans that if successful would reduce the likelihood of the risk and / or lessen the impact if the risk was to become an issue.

Plans must become tasks with the same importance as any other project task and should be stated during normal project rhythms. If action plans are not treated seriously, given the right priorities for budget and resources, and discussed / tracked, all the hard work to this point would be lost.

When developing action plans, there are several options that could be leveraged. See the below picture of Figure 55 [94]

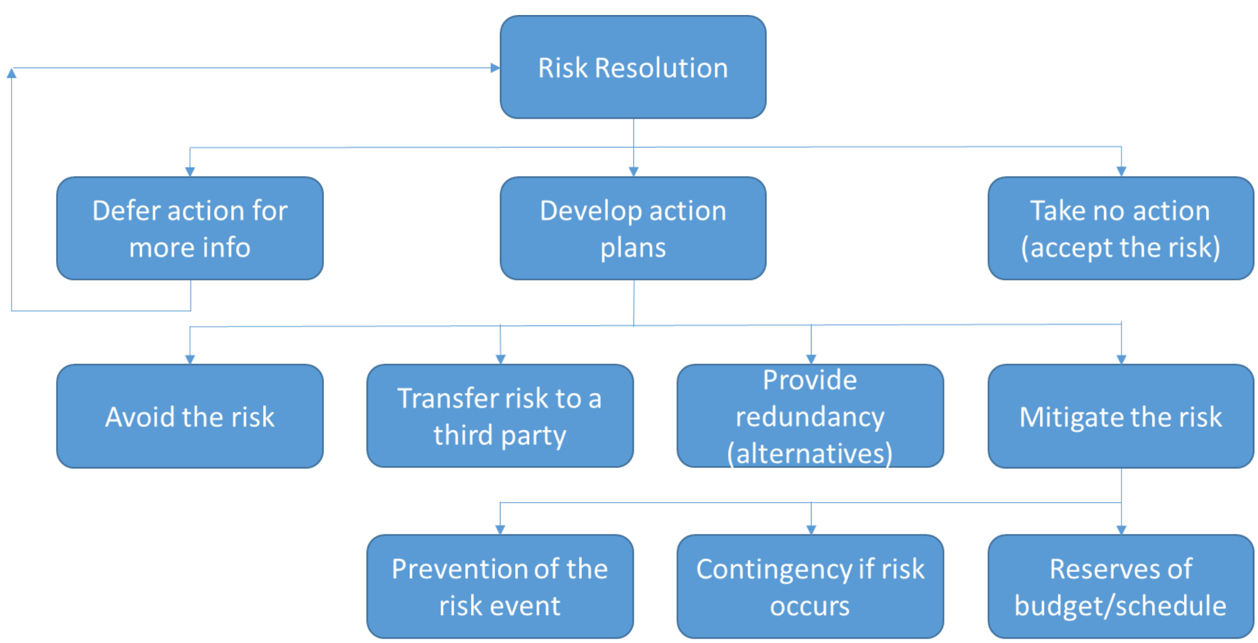

Figure 55: Risk Resolution

In summary, action plans can be cyclic, in that the project manager may choose to close plans or develop additional plans for risks as the various assessment tools are you to check the value of the plans. At regular business rhythms, indicators like effectiveness, risk reduction leverage, implementation time, political expediency, or another criterion, must be discussed.

Action Planning

Action plans will be developed for each active risk found for the UAV project – 140, 125,105, and 115. There are a few basic ways to resolve risks; Avoid, transfer, supply redundancy and mitigation. For this project, the mitigation approach was used.

Mitigation plans are the main stay of effective risk management, where root causes of the risk and impact drivers are targeted, and plans developed to prevent the risk from occurring or lessen the impact should the risk become an issue.

As we developed the mitigation plans, the strategy was as follows – prevention plans are developed for the risk drivers and contingency plans are developed for the impact drivers. See the picture below.

For clarity, examples of alternative risk resolution approaches are discussed below.

Avoidance

Risk exists on a project because certain decision was made which introduced that risk. As an example, and on the UAV project, the decision to complete development into location drove the “Availability of Lab Facilities “risk. The risk can be avoided by reversing the decision and deciding to complete development at one facility.

Transfer

During development, the project manager may decide that a low-risk approach would be to have a supplier complete a portion or all the development of a major subsystem of the project. As an example, on the UAV project, the project manager may elect to have the sensing technology completed by a supplier already familiar with LiDAR technology.

Redundancy

The redundancy strategy involves developing a parallel approach for a risk item. In the UAV example, a redundancy plan for risk 105 Funding Availability, would be to secure a parallel funding source so that if the main source became an issue, the project could still be funded at the same or near full funding rate.

In developing the action plans, the following criteria should be observed; the plans should be specific, trigger points should be identified, time and resource requirements should be identified, lastly there should be an assessment of how the probability of the risk and impact would be affected. See below Table 18 for an example of how the risk and impact probabilities were affected for the UAV project.

Table 18: Risk Plan

Risk Identifier	Priority		Risk Owner		Date Opened	Date Closed	Risk Status	Actual Loss	
115	1		Set Crawford		15-Oct				
Risk Event			Impact		Monitor Days	Pe	Pi	Costs Lt	Costs Le
Stake holder at CO / CA Fire Resource will not be			missed critical needs / incomplete objectives		15-Oct	0.4	0.6	$12,000.00	$ 2,880.00
Risk Event Drivers	Prevention Plans		Impact Drivers	Contingency Plans					
					30-Oct	0.2	0.5	$12,000.00	$ 1,200.00
Needs Analysis not completed	Schedule and get comment for meeting with CA Fire / CO Fire representative - 2 hrs @ $100/hr	1	may not be available to complete development in parallel with existing commitments	develop / review WBS - verify resource commitments - 2 hrs @ $100/hr					
Interviewed scheduled during peak demand season					2-Nov	0.2	0.5	$12,000.00	$ 1,200.00

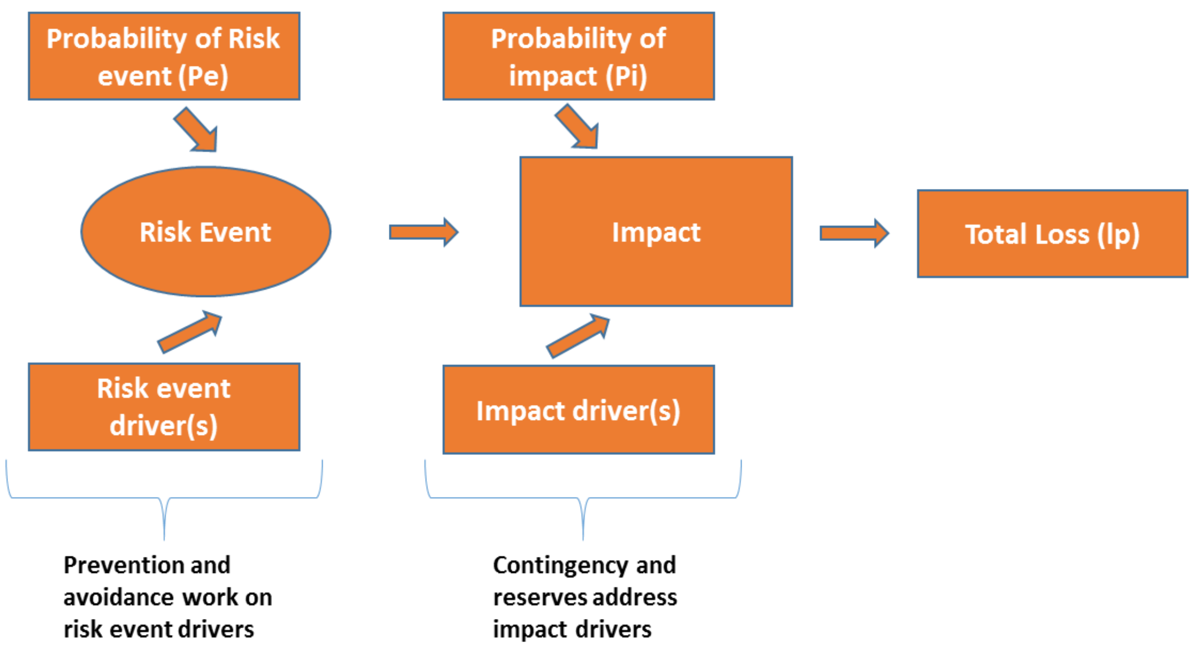

Figure 56: Risk Process – Contingency [94]

Prevention Planning

The first type of mitigation plan work on the risk event drivers and are called prevention plans. There should be at least 5 drivers developed for each of the active risks identified and prevention action plans developed to mitigate those drivers. As stated earlier, there must be logic in the impact drivers which can communicate the calculus of the total loss. The cost of the prevention plan action should also be captured and will be used to compute some risk metrics to be discussed later in the report.

The prevention plans which show how the probability of the risk will be reduced were developed using expert knowledge, a review of similar applications on an adjacent development project and brainstorming. See Table 19 below for risk and impact drivers developed for the UAV project as well as a list of prevention plans.

Table 19: Prevention Planning

Risk ID	Risk Event		Risk Event Drivers	Prevention Plans	Implementation Costs		Risk Reduction Leverage
140	The Sensor Specialist will not be available	1	there is a limited number of sensor specialist resources	contact local college for available experts		$ -	
		2	resources are located at remote sites	offer additional bonus and enhanced travel allowance		$ 1,500.00	2
		3	There is increase demand for sensor specialist	scheduled special travel 2 separate periods- with contingency for cancellation	no	$ 2,000.00	1
		4	ITAR requirements limits use of out of country specialist				
105	Funding Available	1	Needs Analysis not yet completed	Schedule and get comment for meeting with CA Fire / CO Fire representative - 2 hrs @ $100/hr	yes	$ 200.00	12
		2	System Architecture not well defined				
		3	System / Project Costs not yet developed	Research predeccessor system and move forward with ROM for leading concept option - 4 hrs @ $100/hr	yes	$ 400.00	6
		4	Competing initiatives for funding pool				
		5	In ability to convince stake holders of the funding need	Identify back up funding sources - 1 hr @ $100/hr	yes	$ 100.00	23
115	CO / CA Fire Resource Availability	1	Needs Analysis not completed	Schedule and get comment for meeting with CA Fire / CO Fire representative - 2 hrs @ $100/hr	yes	$ 200.00	7
		2	Interviewed scheduled during peak demand season				
125	There maybe a FAA regulation change - max operational altitude	1	max operational altitude for commercial UAV operations 400 ft AGL	hire addition specialist to create design options for operation at different altitudes - contract specialists - $3000	no	$ 2,000.00	1
		2	FAA may require separation of UAVs by altitude much like conventional aircrafts				
		3	altitude may have to follow the direction conventions as with full scale aircrafts				
		4	increase Altitude separation equipment installations onto the UAV	increase time in detail design to develop a more configurable design -20 hrs X $100/hr	no	$ 2,000.00	1

Contingency Planning

The second type of mitigation plan is the contingency plan developed to operate on the impact drivers. Like with the risk drivers, there should be a suitable number of drivers identified, and calculus shown to identify the total loss. Contingency plan should also be assessed to quantify the reduction in probability of the impact and consequence of the impact. See below table for a list of risk event and impact drivers. See table below for a list of contingency plans for the UAV project. Here again, the cost of the various actions is capture.

Table 20: Contingency Planning

Risk ID	Risk Impact		Impact Drivers	Contingency Plans	Implementation	Costs	Risk Reduction Leverage
140	interface definitions maybe inadequate	1	increased iteration in advanced development - project delay - carrying cost of development staff - 50hrs X $200/hr				
		2	move forward with design assumptions - if incorrect will lead to additional time for design and test resources	increase level / detail review during PDR - additional 4 hrs at $100 / hr	yes	$ 400.00	6
		3					
105	Not able to integrate payload compliment	1	Payload sensors are the most costly components	investigate sensors MODIS / LiDAR secure cost estimates - 2 hrs @ $100/hr	yes	$ 200.00	12
		2	May have to implement either sensing or communications components				
		3	Cost of components UAV required - $20000				
		4	Cost of components Satellitle required - $400M				
		5	Cost of components Hosted Payload - $20M				
115	late integration	1	may not be available to complete development in parallel with existing commitments	develop / review WBS - verify resource commitments - 2 hrs @ $100/hr	yes	$ 200.00	7
125	Inability to operate the UAV at an altitude which would allow efficient collection of data	1	added developmental schedule / other unique resources = hire contract specialist - $6000	hire contract specialist - $6000	no	$6,000.00	0
		2	Have to hire a lobbist to work with the FAA and EAA to partition for reasonable operating altitudes	hire lobbist - 4 hrs @ $100/hr	yes	$ 400.00	3
		3	Have to hire specialist conduct research on data collection	research sensing technology options - 2 hrs @ $100 / hr	yes	$ 200.00	6

Reserves

Project teams, very often mistakenly associate the budget allocated for contingency plans with all reserves required to manage any risk that becomes an issue.

Reserves are to be held to cover the following items: unknown risks which will cover, impacts that still occur despite the contingency plans introduced and for inactive risks identified by the team. An accepted rule of thumb is to hold 10% to 20% of the identified budget in reserve, for unknown unknowns.

To determine reserves required for the UAV project, a simulation run Monte Carlo analysis was conducted, given the cost of the mitigation plans and the likelihoods of three of the four active risks. Reference Table 16

Table 21: Risk Simulation

	Risk	Best Case Expected Loss Post Prevention Plan Implementation	Average	Worst Case Expected Loss before prevention Plan
	140	$ 1,950.00	$ 3,075.00	$ 4,200.00
	105	$ 1,672.00	$ 2,836.00	$ 4,000.00
	115	$ 1,040.00	$ 1,720.00	$ 2,400.00
	125	$ 450.00	$ 1,275.00	$ 2,100.00
Totals		$ 5,112.00	$ 8,906.00	$ 12,700.00

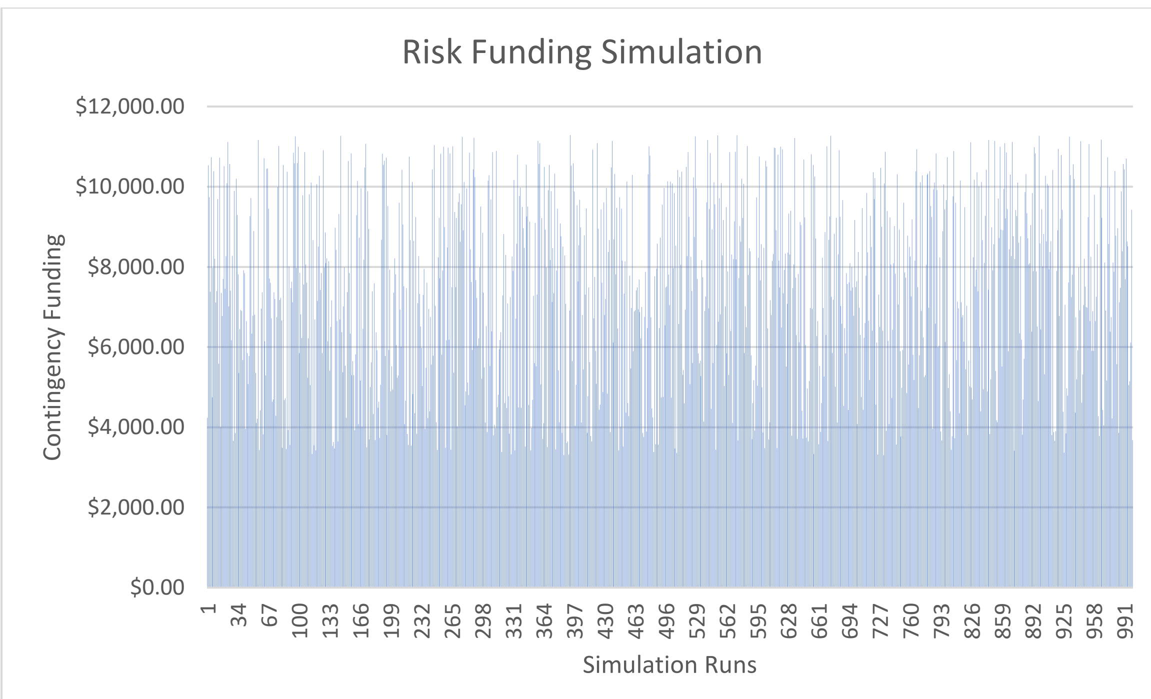

Figure 57: Risk Funding Simulation

Risk Study Summary

Early research results show that the leading concept for fire detection and communication is the H- UAV concept. This configuration could be outfitted with a remote sensing payload complement based on steerable LiDAR technology with associated functional equipment such as (GPS and IMU) is the leading concept.

To improve the likelihood of success, proactive risk management based on the standard risk model and utilizing tools discussed in text “Proactive Risk Management” by Preston G. Smith and Guy M. Merritt”, will be an integral part of all phases of the project from concept exploration through to post development and detailed design activities.

The total of nine project risks were found for the UAV project, of which, five were identified to manage proactively. The five project risks were prioritized by expected loss value in descending order. A threshold value was established and vetted with the major stakeholder and used to determine which of the five risks, the team would actively work, and which would be inactive. Using these guidelines, three of the five risks were identified for active risk management and the remaining two would be inactive but placed on a watch list to be elevated to active status if the threshold value was exceeded. The active risks in order of priority are 140, 105, 115 and 125.

Lessons learned during the project were the importance of identifying a suitable number of drivers for the both the risks and the impact, the importance of the final step in the process – monitoring and setting an appropriate threshold value (10% of the project value). To that end, three to five drivers were developed for each of the active risks and associated impacts. The drivers contained the calculus of the total loss and were numerous enough to allow for good depth in prevention and contingency action plans.

The last step in the risk management process is unlike the other four steps in that it is repetitive. Risk status is reviewed along with other metrics at regular project rhythms and risk are retired if the event time horizon for the risk has passed or the risk became an issue. Other risks maybe added during this step because prevention actions sometime introduce additional risk.

Chapter 6

Reflections, Summary and Conclusion

Reflection on integrating MBSAP &MBSE Tools (Cameo Systems Modeler, @Risk & MATLAB)

As stated previously, a primary tenet of MBSE and this architecture centric method, is that the dimensions and behaviors of a system or system of systems can be captured by graphical and mathematical models. The artifacts we created for this project are useful stand-alone, but the major benefit is what emerges from having to follow the MBSAP framework and creating MBSE artifacts.

The framework and tools force us to obey systems thinking principles and follow the ways of the systems thinker.[115] For example, see Figures 26 and 27 absolutely ensure that we do not purely focus on the internal design features of the H-UAV, the System of Interest (SOI) while ignoring the interactions within and between the SOI, Enabling Systems and System Context: For example, it is nearly impossible to ignore the Holism Systems Principle and miss the associated requirements, when we follow the MBSAP framework and use the MBSE tools.

While the artifacts are interesting and useful stand-alone, they can be created using classical documents or requirement-centric frameworks and tools. However, the Architecture centric approach of MBSAP/MBSE has the advantage that the team members can for example more easily see the impact of architectural changes to the relevant requirements and vice versa. In addition, since the artifacts are digitally interlinked, it is easier to navigate from one viewpoint to another or easily see the impact of changes in one view to another. This enables us to always consider multiple perspectives as opposed to limits a requirements/document centric approach involves.

Specific benefits we experienced in this project are:

- better communication/ synchronization.
- reduced risk in missing key requirements.
- completeness/correctness of systems architecture and design.
- Ease of use of a set of interlinked models and artifacts that allow changes in one to propagate to others.

An excellent example of the utility of the MBSAP framework and MBSE tools is that we discovered a redundancy in the impact of the lift fan and thrust vectoring nozzles on roll, pitch, and yaw response of the H-UAV in Figure 24, that is a function normally allocated to classical flight control surfaces ailerons, elevators, and rudder. The integrated architecture model quickly showed that the specific cost of the H-UAV (a combination of aerodynamic, payload weight, and cost measures) has the potential for drastic reduction below the values shown in Figure 25 if differential control of the fans together with the thrust vectoring nozzle could meet the stringent flight controls requirements in gusty environment of the FDC H-UAV.

MATLAB and @Risk were used to animate the executable model by running simulations to confirm the behaviors versus system operational requirements. Once the digital interfacing standards are adopted more widely, we expect that integrating these tools into the interconnected architectural model will greatly enhance the utility of the interconnected architecture model.

This application of the MBSAP method and the resulting complement of interlinked artifacts and executable models are systems agnostic or not domain specific. The Service Oriented Architecture created for this research describes an architectural pattern which can be applied to other enterprise and UAV systems research with equal efficacy. For example, many of the structure, behavior, requirements, sizing, and validation patterns in the architecture model in this paper would be reusable or modified easily for other autonomous UAVs built for a different mission.

Reflection on Aspect Ratio

Aspect ratio is the ratio of the square of the H-UAV wingspan and the wing surface area. Higher aspect-ratio yield high L/D, lower induced drag, and better range performance. The Fire detection and communication H-UAV has a high design aspect-ratio for range performance. Designs with an aspect-ratio greater than 4 is consider high.[22] Further, the H-UAV utilizes wing mounted (EM)s thrusters with propellers for VTOL operations. The incorporation of the (EM)s and propellers into the wing structure leads to an increase in the wing root dimension and a lower aspect ratio The final aspect ratio was a result of the constraint for the incorporation of the EM propellers, positioning of the spar structural elements, fan doors and the need to improve aerodynamics for the range requirements. Reference chapter 4 Figure 40.

Reflection on Jettison Option

From the range equation EQ 5 chapter four and reference [22], the segment weight has a first order effect on the H-UAV. If we could jettison the battery pack for loiter operations, the loiter range of the H-UAV would increase significantly. This concept would limit the landing of the H-UAV to a conventional field and run counter to one of the primary requirements / behaviors which is VTOL operations. Since the EMs and battery pack are needed for both takeoff and landing operations, the jettison option was not considered. Future studies referred to earlier in the text will probe the benefits of integration of the EM services with tradition flight control services with a possible outcome of eliminating some control surfaces or/and reducing the FCS weight which would result in better range for the H-UAV. Another concern would be the fire hazard posed by a jettison lithium-ion battery pack. Reference chapter 4 Table 12

Reflection on Vector Thrust Nozzle

The thrust vector control architecture envisioned for use on the H-UAV is a simple 3 bearing design mechanical manipulation nozzle which redirects the engine exhaust from straight axial to straight vertical downwards. The vector thrust nozzle is not expected to be a major development concern because it is simple and not comparable to a variable geometry nozzle of modern fighter jets that are more complex because they adjust flow direction in multiple axes as well as flow area. Manipulation of the ICE thrust along with the thrust from the wing mounted EMs enables the H-UAV vertical takeoff and landing (VTOL) behavior. The 3BSD mechanism was first invented in the US in the 1960s, implemented on jet aircraft in the 1970s by the former Soviet Union (Yak 141) and finally implemented onto a US fighter jet platform in the 1990s on the X-35.[120] See chapter four topic and listed references for further insights. A variable nozzle is used to adjust the nozzle exit area of a jet engine converting pressure to velocity and maximizing the total thrust developed as a result. Variable nozzles are a great choice to increase jet engine efficiency particularly on engine with after burners.

Reflection on Payload Flexibility

System Flexibility and in particular – Payload Flexibility can be considered a modularity quality attribute. The H-UAV architecture enables modularity/flexibility so that technology improvements and system tailoring, can be easily accommodated. It follows that changes to weight or volume would be analyzed to gauge the effects of system services. The methodologies discussed in chapter four and the inter linked and coupled CAs affords researchers and system architects, the necessary tools to analyze system behavior affects as the architect evolves.[11][90] For example, a payload weight increase of 1 kg or 17%, with the range requirement held constant, results in an increase H-UAV take-off weight of approximately 3 kg or 6.5% and an increase H-UAV cost of $14k USD or 11.4%. The method also shows the sensitivity of key parameters like L/D, Battery energy density, battery mass fraction, and system efficiency. Figures 36 and 37 of chapter show how we can change these key parameters to compensate for the extra payload weight.

Reflection on Scalability

System Scalability is a measure of how well a system can respond to changes to requirements or cost. This an example of a nonfunctional requirement, quality attribute and a measure of architectural openness.[90] There are two fundamental approaches to scalability, vertical and horizontal scalability. Vertical scalability is the increase in system performance because of technology improvements. For the H-UAV, this could be an increase in battery specific energy, L/D, high efficiency ICE, a larger UAV and or some combination of services resulting in a reduction in system weight and improved range performance as a result. Researcher can use the method to analyze effects of these technology changes on key system behaviors. For example, changes in L/D could result in changes to the H-UAV specific costs from $145 kg/km to $211 kg/km and a corresponding range impact of 116 km to 162 km. Reference Figures 37 and 44. Horizontal scalability is adding more capability by scaling up (larger dimensions, weight, and larger fuel tanks etc.) or adding more UAVs to the operating fleet. The fire detection and communication system design are based on 2 UAVs, however, the method considered 1 to 3 UAVs. This number can be increased and would require further packaging optimization constrained by the capabilities of the mobile base station (truck) to carry additional H-UAVs.

Reflection on Public as stakeholder
Health and Safety

Modern systems instantiation needs analyses must consider the public as stakeholders for a complete complement of system requirements. Excluded from considerations are any unknown or upcoming FAA regulations on the use of UAV in remote forest areas. The H-UAV uses a LiDAR payload for fire detection and communications. LiDAR is a remote sensing technology that measures distance by illuminating a target with laser light and analyzing the reflected light to build a bitmap of the target area. Several different wavelengths are in use today; however, this application will focus on longer wavelengths (eye safe), 1,550 nm. The human eye cannot focus on this wavelength which has the added benefit of not being visible by night vision goggles. Additionally, this wavelength allows for maximum energy while still human eye safe and the longer wavelength have less molecular scattering and lower radiance contribution, which leads to better measurement contrast and greater signal-to-noise ratio.[121]

System noise and Noise reduction technology is another public health concern. To address this concern, The H-UAV turbine ICE could have a takeoff and landing noise emission of 140 to 160 db. [122] A blended wing body with internal ICE and engine exhaust flow augmented by vector nozzles concept is part of the architecture. This configuration could yield as much as 42 dB reduction in noise.[122][123]. Air attenuation – Stoke law could yield another 10 dB reduction so that- during loiter at the design mission sensing altitude of 2000 meters above ground level, public sound perception would be no greater than normal conversation levels.

Societal Benefits

Wildfires have been on the increase in frequency, duration, and intensity worldwide. In the Western United States, wildfires can release as much carbon dioxide into the

atmosphere in a week as all the automobiles in the region for an entire year. Results suggests that there will be benefits to society. The H-UAV system will assist in the reduced time for detection of wildfires and is especially helpful in the estimation of the amount of vegetative fuel and climate measurements that can influence and affect the intensity, direction, and potential devastative effects of wildfire. Clearly, in wildfire-prone areas. H-UAV technology is a suitable addition to the arsenal of wildfire detection and suppression. Another tangible benefit is affordability, the H-UAV is an affordable platform which meets stakeholder requirements for a locally owned and operated fire detection and communication agency, without relying on major investment in airstrips infrastructure. Further, we used the MBSAP framework and MBSE tools (Cameo Systems Modeler, @Risk and MATLAB) to approach the UAV-based Wildfire Detection and Communication complex problem. We report on the approach and present the reader with all the relevant artifacts including design patterns that can be used to develop UAV-based solutions for other challenging problems or purposes.

Reflection on Coupled Architecture / Executable Model / Executable Architecture

Executable Architecture 'Represents *the architecture in the form of computer models that can be animated to simulate system behaviors, perform automatic code generation and verify design corrections*".[90] A variety of tools were used to animate the H-UAV executable model /coupled architecture to confirm that system behaviors were consistent with stakeholder requirements. MATLAB, @RISK, Excel and Cameo were used to animate portions of the coupled architecture and generate statistics to visualize system sensitivities. Although, not fully executable, in that the cameo artifacts are not linked to the CAs and at-risk, the coupled architecture / executable model (at-risk is linked to the Excel CAs and the Cameo artifacts are interlinked), offers some proof of the benefits of a fully executable architecture. The linking of the Cameo artifacts, at-risk and Excel CAs to achieve a fully executable architecture will be address with future work.

Summary and Conclusion

Implementing the MBSAP structured approach to the wildfire detection and communications systems engineering research, and in particular, the service orientation, enabled the appropriate trade analyses and collection of comprehensive functional and non-functional requirements, those requirements were mapped to behaviors which led to services and formed the basis for the development of goals and scenarios, which in turn captured critical enterprise and subsystem behaviors.

The trade study, chapter 2 [7] found that a small fleet of VTOL H-UAVs, transported to the edge of the forest on the back of a mid-size truck, would likely beat other land-, air- and space-based architectures developed for the purpose of detection and communication of wildfires. The next step: was the development of an executable model formed by the integration of MBSAP with Design Space Exploration. System behaviors were validated by animating the executable architecture to conduct simulations. The results of multiple simulations during the Design Space Exploration (DSE) phase of the research, further substantiate, the initial finding of the trade study.

This helped us find the optimal design size, weight, cost, and performance of the H-UAV, in addition to the sensitivity of range, weight and cost to major design drivers and technology measures.

Given that the severity and adverse impact of wildfires is growing in the US and the World, the good news is that this work has identified a feasible low-cost, locally owned, and operated VTOL H-UAV concept shown in Figures 40,41 and 42 that meets stakeholder needs and operational requirements, using only current levels of technology and off the shelf components such as battery, lift fans, gas turbine, ducting, fuel tank and nozzle etc.

The Monte-Carlo sensitivity results also identified at least four realistic directions for improving the specific cost well beyond the 182 $/(kg.km) of the current technology baseline H-UAV. These directions are scaling up the gross take-off weight, increasing climb velocity, increasing L/D and Wing Area in ranked order.

This work also showed that an E-UAV of a similar architecture would in principle become feasible, if the expert estimates on best future practical battery energy density and battery mass fraction are realized in practice. We have not yet found a scenario or architecture where the E-UAV weight, range, or cost shines relative to the H-UAV.

Furthermore, this body of work shows that the MBSAP method is systems/application agnostic: i.e., equally applicable to systems that have significant software, electronic and mechanical hardware content.

This research also considered programmatic risks for a UAV development. The risk method presented in chapter 4 is intended to present an example approach to risk management for a UAV development program and address the NRE component of affordability, whereas chapters 1,2 and 3 addressed the UAV block affordability.

Research Contributions

Trade study of different platforms used for wildfire detection and communication leading to a new understanding of the benefits of proactive vs reactive mitigation strategies.

- Scholarly review of current UAV literature leading to new understanding of hybrid electric propulsion system / UAV aerodynamic synthesis.
- Developed New Method for sizing UAV Hybrid Electric propulsion systems.
- Review of MDSO techniques and applications to UAV systems architecture.
- Review of energy storage technologies and applications to UAV systems
- Review of Electric Motor Technologies and applications to UAV systems.
- Review of small turbine engine technology and applications to UAV systems.

Future Work

Wildfires are often coincident with harsh flight dynamic conditions. The H-UAV needs a flight control system capable of flying through, take-off and landing in very rough weather. While we accounted for fight controls components in terms of size, weight, and cost, we still need to prove that the H-UAV can manage rough weather. We have already started working on this question: would using the Fan-in-Wing in combination with vectored thrust result in sufficient control through all phases of the mission in rough weather, and how it trades-off versus classical flight control surfaces.

We also need to add higher fidelity optimization of the 3D structure and aerodynamics to find and resolve any detail design issues prior to building a flying prototype.

We also need to overcome the sensor integration/fusion to ensure that the integrated (LiDAR/FLIR, Camera) package stays below 6 kg useful payload allowance and fits properly in the frontal section of the fuselage.

Further, one of the efficiencies mentioned earlier is using a service-oriented approach where request for services is made node agnostic. In keeping with this philosophy, perhaps a future study could look at the continued viability of a terrestrial based fire detection system as opposed to getting that same service from a proliferated LEO satellite system as an adjacent application. The cost of satellite-based systems can be in the $10Ms to $100Ms of dollars. However, if they have already been put into service for some other primary need, or in other words already financed, it might be possible to integrate their capabilities into a cost-effective wildfire detection and communication system.

This research focused on an element of the fire detection and communication enterprise, the H-UAV, perhaps, a future project could focus on cybersecurity and or other aspects of the enterprise.

Data Availability

The data used to support the findings of this research thesis are available upon request.

Conflict of Interest

All data, methods and artifacts of this paper are the result of PhD level research by the authors at the Colorado State University Systems Engineering Department.

The authors declare that there are no conflicts of interest regarding the publication of this thesis.

Disclaimer

The views and opinions expressed in this dissertation and trade study analyses are solely the authors. The views and opinions do not represent any position of the Lockheed Martin Corporation, National Aeronautics and Space Administration (NASA), Colorado State University, any employment entity, or any other organization, group, or individual.

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Acronyms and Nomenclature

3BSD = 3 Bearing Swivel Duct

A = Area, [m^2]

AD = Activity Diagram

AR = wing aspect ratio, [-]

A1 = Nozzle area of jet engine, [m^2]

BDD = Block Definition Diagram

BEP = Battery Electric Power

BLDC = Brushless DC Motor

BLI = Boundary Layer Ingestion

BUS = UAV Structure

C = Battery Charge Coefficient, [-]

CA = Contributing Analysis

DL = Disc Loading, [kg/m^2]

D = Drag, [N]

DiD = Defense In Depth

DSE = Design Space Exploration

DT = Digital Twin

E- UAV – Battery Power UAV

EM = Electric Motor

$\mathbf{E_{climb}}$ = Energy storage to climb (fuel and battery), [J]

$\mathbf{E_{dash}}$ = Energy storage to dash (fuel), [J]

$\mathbf{E_{hover}}$ = Energy storage to hover, [J]

$\mathbf{E_{loiter}}$ = Energy storage to loiter (fuel), [J]

Etot = Total Energy storage onboard the UAV – Battery plus Fuel, [J]

FC-UAV = Fuel Cell UAV

FD&C – UAV = Fire Detection and Communication UAV

FLIR = Forward Looking Infra-Red

FoM = Figure of Merit

FR = Functional Requirement

GEO = Geosynchronous Earth Orbit

GSO = Geosynchronous Orbiting Satellite

GRG = Generalized Reduced Gradient

H-UAV = Hybrid Battery / Turbine Power UAV

HOAV = Human Occupied Air Vehicle

ICE = Internal Combustion Engine

IDS/IPS = Intrusion Detection System

IMU = Inertial Measuring Unit

IR = Infrared Sensor

ISR = Intelligence Surveillance Reconnaissance

K = Induced drag coefficient, [-]

Kg = Kilograms

Km. **KM** = Kilometers

L = Lift, [N]

LEO = Lower Earth Orbit

LiDAR = Laser Detection and Ranging

LiS = Lithium Sulfur Battery

LV = Logical Viewpoint

MBSE = Model Base Systems Engineering

MBSAP = Model Based Systems Engineering Architecture Process

MDA = Multidisciplinary Analyses

MIB = Management Information Base

MODIS = Moderate Resolution Imaging Spectroradiometer

MoE = Measure of Effectiveness

MSG = Meteosat Second Generation

M&S = Modelling Simulation and Analysis

MSDO = Multidisciplinary Systems Design Optimization

NFR = Non-Functional Requirement

nm = Nautical Miles

OV = Operational Viewpoint

PA = Power available, [W]

PL = Power Loading, [W/kg]

PR = Power Required, [W]

PV = Physical Viewpoint

R = Range, UAV Loiter Range, [km]

RMA = Reliability Maintainability and Analysis

RoC, $\boldsymbol{R/C}$ = Rate of Climb, [m/s]

RPM = Propeller Revolutions per Minute

S = wing surface area, [m^2]

SOA = Service Oriented Architecture

SMD = State Machine Diagram

SNMP = Simple Network Management Protocol

T = Temperature, Thrust, [deg C],[N]

TOGR = Take Off Ground Roll

TSFC = Thrust Specific Fuel Consumption

TVC = Thrust Vector Control

UAS = Unmanned Aircraft Systems

UAV = Unmanned Aerial Vehicle

UC = Use Case

UTM = Unified Threat Management

VTOL = Vertical take Off and Landing

W = weight of the UAV, [kg]

W/P, PL = Power Loading, [W/kg]

$\boldsymbol{W_0}$, , **WT0** = Take-off weight (initial weight), [kg]

$\boldsymbol{W_1}$ = Final Segment Weight, [kg]

Z = Variable Introduced for Presentation Simplicity, [-]

$Batt_{mass_{ER}}$ = Battery Mass for Energy Requirement, [kg]

$Batt_{MF}$ = Battery Mass Fraction, [kg]

$Batt_{Sys\_W}$ = Battery System Weight, [kg]

$Batt_{mass_{PR}}$ = Battery Mass for Power Requirement, [kg]

$Batt_{ED}$ = Battery Energy Density, [Wh/kg]

$Batt_{PD}$ = Battery Power Density, [W/kg]

C_D = Total drag coefficient, [-]

C_d = drag coefficient, [-]

$C_{D,0}$ = zero lift drag coefficient. [-]

C_E = UAV Climb Energy Required, [W]

C_L = lift coefficient, [-]

C_{Lmax} = Maximum lift coefficient, [-]

C_P = UAV Climb Power Required, [W]

$\boldsymbol{c_t}$ = Thrust Specific Fuel consumption, [N/N-s]

D_{UAV} = UAV Drag, [N]

$\boldsymbol{e_{C\_d}}$ = Battery Charge / discharge Efficiency, [-]

k_i = Induced Power Correction Factor – typical value 1.15 [22], [-]

K_{Inlet} = Air Inlet factor (complexity of the engine inlet design), [-]

$\dot{m}_{air}$ = mass of air flowing through the jet engine, [kg/s]

$\dot{m}_{fuel}$ = mass of fuel flowing through the jet engine, [kg/s]

$\boldsymbol{M}_\infty$ = Free Velocity Mach number, [-]

P_{acc} = Power for accessories, [W]

P_{Batt} = Battery Power, [W]

P_c = Power for climb, [W]

P_{charge} = Power to charge battery, [W]

$\boldsymbol{p_e}$ = Exhaust gas pressure at nozzle exit, [kg/m^2]

P_{fcs} = Power for flight control system, [W]

P_i = Power Induced, [W]

P_0 = Profile Power, [W]

P_p = Parasitic Power, [W]

P_{pay} = Power for Payload, [W]

P_{TR} = Power for Tail rotor, [W]

P_T = Power Generated by Propulsive Device, [W]

P_{UAV} = UAV Power, [W]

$\boldsymbol{P_\infty}$ = Ambient pressure, [N/m^2]

$\boldsymbol{q_\infty}$ = dynamic pressure, [N/m^2]

S_{wet} = Wetted surface area, [m^2]

S_ω = Wing Surface Area, [m^2]

T_A = Thrust Available, [N]

$T_{A\,max}$ = Max Thrust Available, [N]

T_0 = Thrust Sea Level, [N]

T_R = Thrust Required, [N]

$V_{\left(C_L^{1/2}/C_D\right)_{max}}$ = Velocity Max Range – Jet Propelled UAV, [m/s]

V_i = induced velocity at propeller disc, [m/s]

V_j = Exhaust velocity of jet engine, [m/s]

V_{max} = Maximum Forward Velocity, [m/s]

$V_{(R/C)_{max}}$ = Velocity to achieve Max Rate of Climb, [m/s]

V_{tip} = propeller tip speed, [m/s]

V_y = Forward velocity which makes the UAV flight wing borne, [m/s]

$V_{y,c}$ = rate of climb at service ceiling, [m/s]

V_{yc} = rate of climb at service ceiling, [m/s]

$V_\infty(L/D)$ = Velocity at Max Lift to Drag Ratio, [m/s]

V_∞ = Freestream velocity, [m/s]

W_{AI} = Air Induction System Weight, [kg]

W_{ES} = Electrical Harness Weight, [kg]

W_{Emp} = Weight UAV Empennage, [kg]

W_{ESC} = EM Controls System Weight, [kg]

W_{FCS} = Control Systems Weight, [kg]

W_{FE} = Fixed Equipment Weight, [kg]

$\dot{W}_f$ = Rate of change of UAV Weight, [kg]

W_{Fuse} = Weight UAV Fuselage, [kg]

W_{LG} = Weight UAV Landing Gear, [kg]

W_{Nac} = Weight UAV Nacelle, [kg]

W_{PL} = Payload Weight, [kg]

W_{PI} = Propulsion System Installation Weight,[kg]

W_{PP} = Power Plant Weight, [kg]

W_{Strut} = Weight UAV Structure, [kg]

W_{Wing} = Weight UAV Wing, [kg]

W_{WingC} = Weight UAV Wing – Chun's Eq, [kg]

W_{WingR} = Weight UAV Wing Roskam's Eq, [kg]

W_{Wing} = Weight UAV Wing, [kg]

W_{IAES} = UAV Navigation and Flight Control System Weight, [kg]

$\boldsymbol{W}/\boldsymbol{S}$ = Wing Loading,[kg/m^2]

ε = Oswald span efficiency, [-]

θ_{max} = Maximum angle of climb, [deg]

$\boldsymbol{\rho}_\infty$ = air density at the segment altitude, [kg/m^3]

$\boldsymbol{\rho}$ = air density, , [kg/m^3]

$\boldsymbol{\rho_0}$ = air density at the sea level, , [kg/m^3]

μ = Advance ratio [-]

σ = Propeller Solidity Ratio; Design Ultimate Loading [-]

$\boldsymbol{\eta_{prop}}$= Propeller efficiency, [-]

$\boldsymbol{\eta_p}$= Propulsive efficiency, [-]

$\boldsymbol{\eta_{tr}}$= Transmission efficiency, [-]

$\boldsymbol{\eta_{total}}$= Total System efficiency, [-]

$\boldsymbol{\sigma_{air}}$ = EM derating – accounts for decrease heat dissipation with increase altitude, [-]