Wildfire Detection and Communication–Aerospace Applications–Trade Study

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■ ABSTRACT

Wildfires have increased in frequency, duration, and intensity worldwide. Climate change, drought, and other factors have not only increased susceptibility to wildfires, but have also increased the duration of the season. There are a number of factors affecting wildfires: detection, speed of communication/response time, resources/politics/climate change/infrastructure to fight fires, and prevention education. A wildfire doubles in size and intensity every 3 to 5 minutes and response times tend to be 10 to 15 minutes at best. The goal of the trade analysis is to arrive at a cost-effective and robust performance system which can be operated at the county level with minimal infrastructure to mitigate the menacing problem of forest wildfires. The approach will be a disciplined systems engineering approach to objectively arrive at the best solution for detection and communication of wildfires, having analyzed the measures of effectiveness (MOEs) for all critical requirements for a technologically diverse set of solutions. Though the analysis is still at a very early stage and the outcome could change as additional details are developed, due diligence was exercised in the evaluation of parameters such as detection time, total operations cost, and operational flexibility, to name a few. Early trade-off results indicate that the lead concept is a rotor-wing unmanned aerial vehicle (UAV) concept, utilizing a rotorcraft configuration which could be outfitted with a remote-sensing payload compliment based on light detection and ranging (LiDAR) technology with associated functional equipment such as global positioning systems (GPS) and inertial measurement units (IMU). The UAV would be semiautonomous, launched from and remotely controlled by an operator in the general area of interest. Upon arriving at this area of interest, the UAV would then fly a flight plan autonomously to collect and communicate data to a base station to be used to direct wildfire mitigation services in the event of a positive detection.

INTRODUCTION

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 doubles 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 1 on the next page for the projected growth of the 10-year average cost of fire suppression (in 1000 USD) through 2015.

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 methodical 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

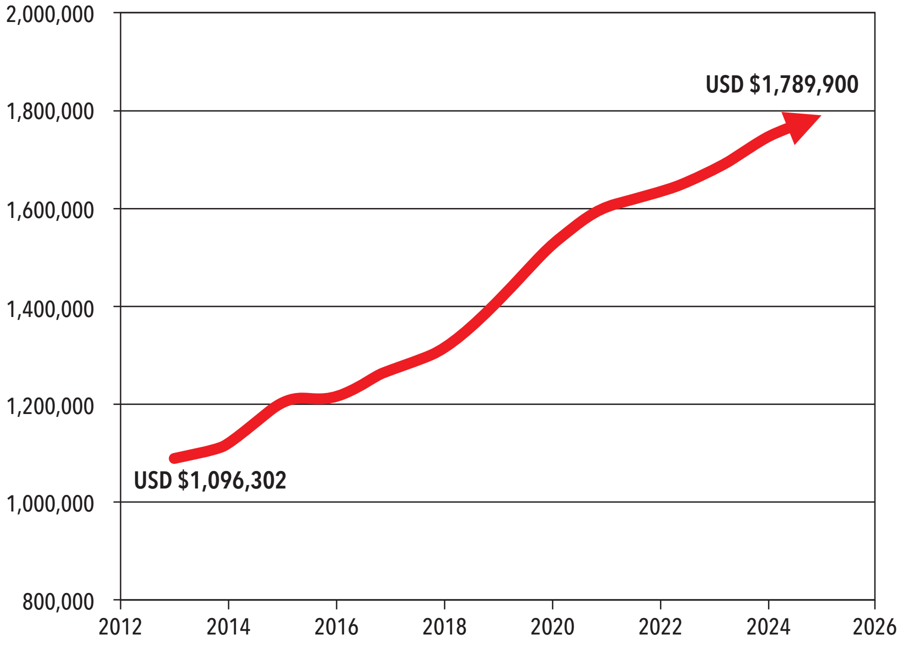

*Figure 1. Projected growth of the 10-year average cost of fire suppression (in 1000 USD) through 2015 (*https://www.fs.fed.us/sites/default/files/2015-Rising-Cost-Wildfire-Operations.pdf*)*

- a concept exploration phase, where we will consider an appropriate amount 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 indicate that the leading concept for fire detection and communication is the UAV rotorcraft concept. A rotorcraft 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.

DISCUSSION

Trade Study Strategy

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.

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 re-examine the benefits of a rotor-wing versus fixed-wing UAV configuration.

Testing/Verifications

The objective of testing and validation is to complete several levels of components and systems testing by using a surrogate platform to test 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 surveillance passes required, and by extension, decrease 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.

Table 1. NOAA AVHRR (http//noaasis.noaa.gov/NOAASIS/ml/avhrr.html)

AVHRR/3 Channel Characteristics

Channel number	Resolution at nadir	Wavelength (μm)	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 temperature
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

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).

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. 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%.

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 the area of mission planning to reduce detection time. We can reduce the particular 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.

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. We used brainstorming and the Delphi technique to yield these concepts. Realizing the importance of technology diversity as well as a balanced risk tolerance, we used expert knowledge review 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 exactly 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 a figure eight form. Its precise characteristics depend on the orbit's inclination and eccentricity.

Table 2. GOES-15 Characteristics (http://noaasis.noaa.gov/NOAASIS/ml/genlsatl.html)

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: 8.2 m (26 ft 9 in) Width – Antenna: 2.25m x 3.37m (7ft 4 in x 11 ft)
Weight at liftoff:	7,136 lbm (3,238 kg)
Launch vehicle:	Delta IV
Launch date:	March 04, 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)

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.

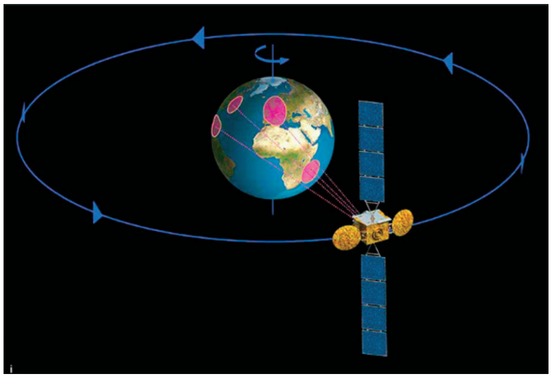

Figure 2. Geosynchronous earth orbit satellite (https://thecuriousastronomer.files.wordpress.com/2014/11/geostationary_orbit.jpg)

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 large portion of this cost is for insurance to cover losses as a result 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 2 and Table 2. 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.

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 very 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

Table 3. *NOAA 19 Characteristics* (http://noaasis.noaa.gov/NOAASIS/ml/genlsatl.html)

Main body:	4.2 m (13.75 ft) long 1.88 m (6.2 ft) diameter
Solar array:	2.73 m (8.96 ft) by 6.14 m (20.16 ft)
Weight at liftoff:	1419.8 kg (3130 lbs) including 4.1 kg of gaseous nitrogen
Launch vehicle:	Delta II 7320-10 space launch vehicle
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)

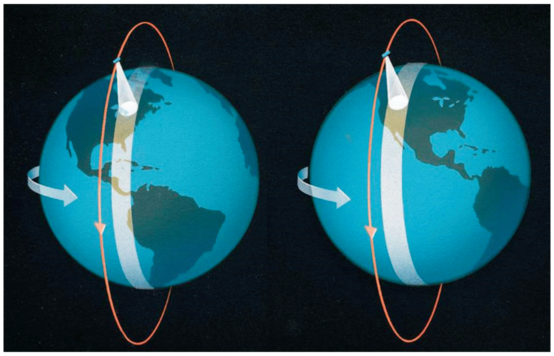

Figure 3. *Polar orbit* (http://apollo.lsc.vsc.edu/)

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 large portion of this cost is for insurance to cover losses as a result of booster failure. Design life is typically 3 to 5 years. See Figure 3 and Table 3. 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.

Hosted Payload Option

A sensor complement payload would be integrated onto a host satellite to be placed into a GEO or LEO orbit (Figure 4). 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. 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.

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 manned aircraft, UAVs are often preferred for missions that are too “dull, dirty, or dangerous” for humans (https://en.wikipedia.org/wiki/Unmanned_aerial_vehicle). 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 wild fire detection UAV system—named “FireCrow”—will be similar in basic architecture to the Meretmarine UAV (see Figure 5), due to the launch and landing flexibility requirement.

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

Figure 4. *Hosted-payload satellite system* (https://www.harris.com/solution/hosted-payload-solutions)

Figure 5. *Rotorcraft UAV with gimballed LiDAR sensor pod* (meretmarine.com)

Table 4. Trade analysis

Measurement	Rank	Concept Options												Comments
		Satellites						UAVs						
		GEO	normal	LEO	normal	Hosted Payload	normal	Rotor-craft	normal	Fixed-wing	normal	Blimp	normal	
Cost (USD K)	10	USD 291,420		USD 281,700		USD 44		USD 120		USD 100		USD 90		USD 8000/lb – target cost USD120K
Affordability		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 USD 3M
Detection	8													
Loiter		1	1	0.5	1	1	1	0.5	0.5	0.75	0.75	1	1	weighting factor
Accuracy		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
Deployment		1	1	1	1	1	1	15	15	0.5	0.5	0.5	0.5	weighting factor–Take off/Landing
Cyber Security	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**	

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 in order to land and take off, whereas a rotorcraft could launch and land from a remote location with minimal infrastructure required.

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 stake holders 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 3 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 3 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 in excess of 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 Figure 6, for popular UAVs and the "FireCrow UAV" system which is the subject of discussion for the UAV portion of the trade study.

Figures 7 and 8 are the proposed architectural block diagram and function flow block diagram, respectively. Given the objective statements—a review of legacy systems and some amount of research—we developed a set of first level requirements. Cost and detection time were the primary requirements. A first level trade analysis resulted in the selection of the UAV concept, given the relative low cost of development and operation of these systems.

UAV Solutions-Oriented Requirements

- R1 – The UAV shall be able to take off and land from remote unimproved locations by utilizing a rotorcraft configuration.
- R2 – The UAV sensor package shall avoid the errors associated with infrared sensors by utilizing a LiDAR sensor package.
- R3 – The UAV shall increase off-nadir sensor capability by employing sensor steering technologies.
- R4 – The UAV shall implement counter rotating main rotors so as to eliminate the need for a tail rotor assembly.
- R5 – The UAV shall employ ADSB technologies to avoid conflicting traffic.
- R6 – The UAV shall have a safe mode flight path algorithm as an option for defense again hacking and hijack of assets.
- R7 – The UAV shall be able to modify its flight path autonomously by utilizing historical data on the area of interest to reduce time of target.
- R8 – The UAV shall be able to complete on board self-diagnostics and communication systems state of health information to the base station.
- R9 – The UAV shall have an availability greater than 95% by utilizing high technology readiness level (TRL) technologies.
- R10 – The UAV shall implement secure architecture strategies to increase resilience to cyber threats.

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).

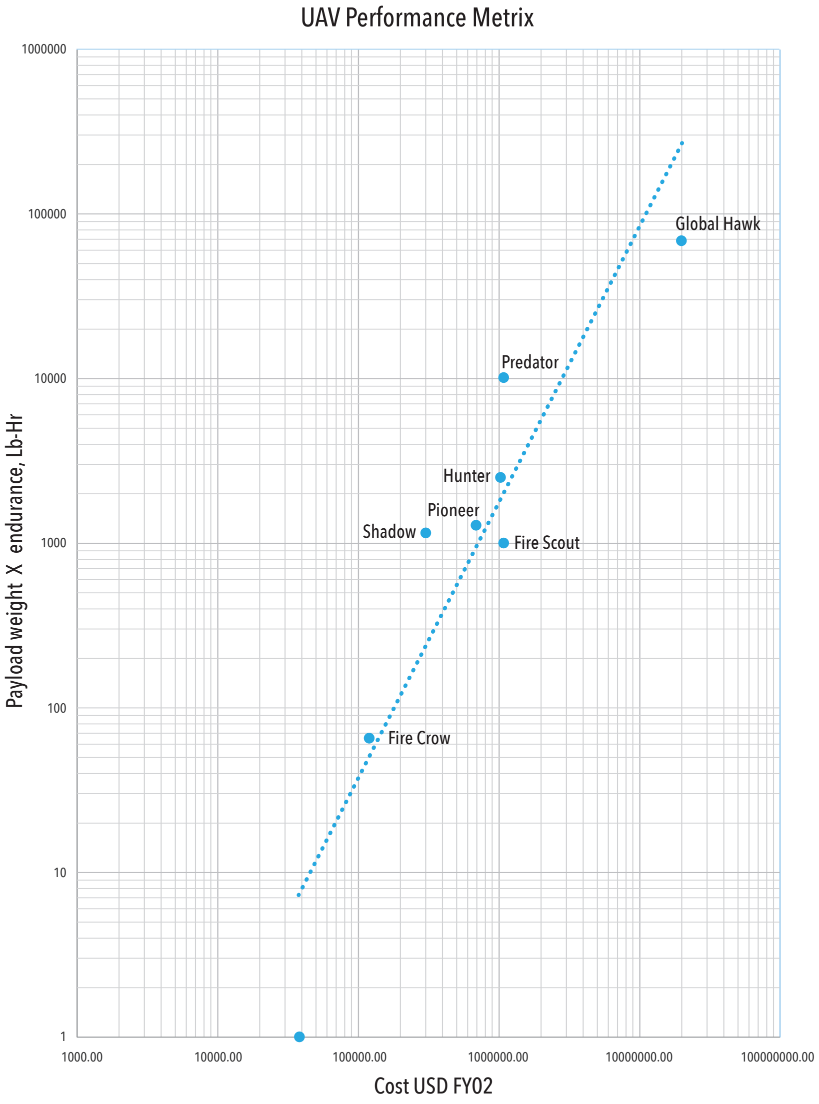

Figure 6. UAV performance mAtrix

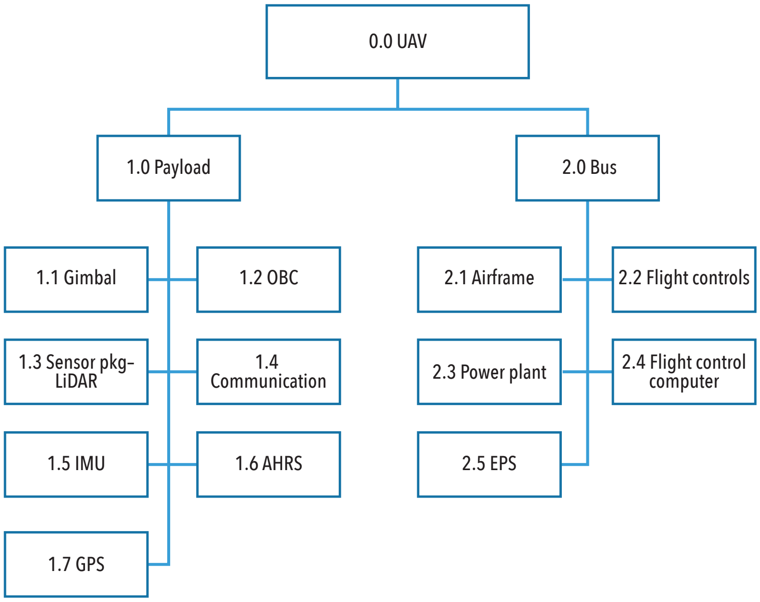

Figure 7. UAV architectural block diagram functional flow block diagram

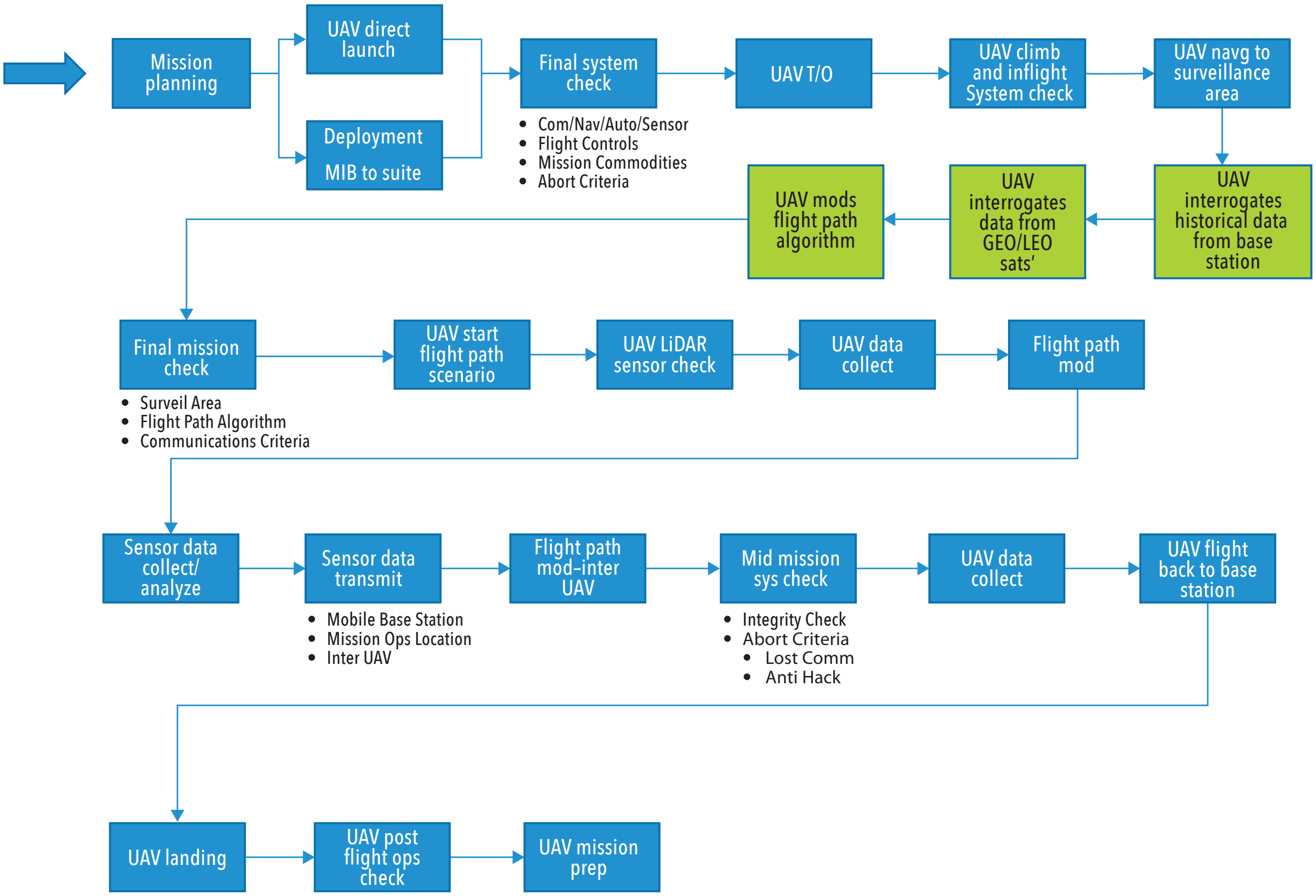

Figure 8. UAV functional flow block diagram

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 "FireCrow" 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.

SUMMARY

Research results to date show that a rotor-wing 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. ▪

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