Use of a Small Unmanned Aircraft System for Autonomous Fire Spotting at the Great Dismal Swamp

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This paper describes the results of a set of experiments and analyses conducted to evaluate the capability of small unmanned aircraft systems (sUAS) to spot nascent fires in the Great Dismal Swamp (GDS) National Wildlife Refuge. This work is the result of a partnership between the National Aeronautics and Space Administration and the US Fish and Wildlife service specifically to investigate sUAS usage for fire-spotting. The objectives of the current effort were to: 1) Determine suitability and utility of low-cost Small Unmanned Aircraft Systems (sUAS) to detect nascent fires at GDS; 2) Identify and assess the necessary National Airspace System (NAS) integration issues; and 3) Provide information to GDS and the community on system requirements and concepts-of-operation (CONOPS) for conducting fire detection/support mission in the National Airspace and (4) Identify potential applications of intelligent autonomy that would enable or benefit this high-value mission. In addition, data on the ability of various low-cost sensors to detect smoke plumes and fire hot spots was generated during the experiments as well as identifying a path towards a future practical mission utility by using sUAS in beyond visual-line-of-sight operation in the National Airspace System (NAS).

Nomenclature

sUAS = small Unmanned Aircraft Systems
NAS = National Airspace System

I. Introduction

According to statistics compiled by the National InterAgency Fire Center, over the last decade fire suppression costs to the Federal Government have averaged over $1.5 Billion per year. Almost 1/3 of the firefighting costs associated with suppressing wild fires falls on the shoulders of the US Department of the Interior agencies, including the US Fish and Wildlife Service.

The US Fish and Wildlife Service Great Dismal Swamp (GDS) National Wildlife Refuge is located in South-East Virginia and North-East North Carolina. The GDS is a national wildlife refuge of approximately 112,000 acres. Lake Drummond is a 3,100 acre natural lake located within the GDS. Overall, the GDS is roughly 20 miles long by 10 miles wide and is considered a southern swamp with many low-lying areas which are inhospitable to ground-based modes of transportation. It is subject to extensive underground fires which cause a great deal of smoke that impacts local communities as well as those living hundreds of miles away. The GDS fires are usually triggered by lightning strikes which initially ignite relatively small surface fires. If the lightning-strike ignited nascent fires are not discovered and controlled, they can potentially burn into the ground igniting the flammable and extremely hard to put out peat moss layer. Fires in 2008 and again in 2011 followed this pattern. These fires burned for weeks and posed an environmental hazard to millions of people. Figure 1 is a photograph of the 2011 GDS fire showing the large amount of smoke generated from this event.

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Figure 1 - Aerial photograph of wild-fires at the Great Dismal Swamp.

The existing fire detection and spotting efforts begin by collecting various sources of data which are processed by the Fire Fighting personnel at the GDS. Elements of data included within the process are the prevailing climactic conditions, which indicate if the swamp is relatively wet or dry, and the type of thunderstorm activity. Thunderstorms with a lot of lightning and not much rain are particularly problematic. If the swamp is considered particularly dry without recent significant rain, then the threat of lightning-induced wild-fires increases.

Whenever a lightning storm crosses through the GDS, a map of lightning strikes is acquired by GDS personnel (Fig. 2). Negative (dashed icons) indicate negatively-charged strikes, positive lightning strikes are presented by red plus sign icons. While there is some debate regarding the energy and temperature of negatively-charged and positively-charged lightning strikes, all are considered to be potential fire starters and need to be inspected. The current fire-spotting process involves use of manned airborne resources to search for fires and focusing on the lightning strike data. Airborne resources typically include small helicopters which are contracted from a local

Figure 2 - Example lightning strike data from July 16th, 2013.

service. Trained GDS fire-fighting personnel go on fire-spotting missions and look for fires using several techniques. In general, fires are spotted by simply looking for smoke plumes. If a fire is spotted, it is more closely inspected from the air. If the fire is considered threatening to spread into the ground, efforts are made to get to the location via ground based methods to control or extinguish the fire. Fires that are less threatening are monitored from the air. Frequently fires burn themselves out with no need to actually travel to the location. In addition to visually unaided aerial fire-spotting, GDS personnel can also use hand-held infra-red (IR) devices to map boundaries.
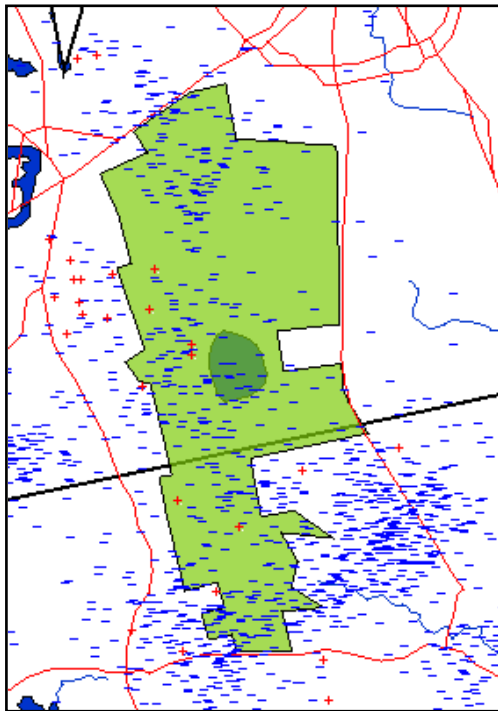
The decision to employ and dispatch the surveillance assets are often weighed against the cost to deploy them. Once the decision is made to employ the airborne assets, the actual aerial surveillance efforts then require helicopter rentals costing ~$1,250/hr along with specially-trained GDS personnel to support the efforts. Generally, the cost per "scan" of the swamp is $4000-$5000 since contractors of this type are inconveniently based over an hour away from the GDS. Aerial surveillance also exposes GDS personnel to some elevated risk associated with the airborne operations. Issues affecting the response time for manned aerial surveillance are that helicopters may not be readily available, minimum weather conditions required for visual flight rules (VFR) helicopter flight may not exist, and specially-trained Fire Fighting personnel may not be available.

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It is considered possible that the GDS could actually own and operate a dedicated helicopter, however, intermittent use would likely not justify the costs of owning and maintaining the helicopter and crew. Contracting helicopter services, as is currently performed, decreases costs since the cost of the vehicle and pilot is shared across multiple users.

II.   Objectives and Technical Challenges

It has been proposed that the aerial fire-spotting tasks at the GDS be performed using Unmanned Aerial Vehicles (UAVs) which are also referred to as Unmanned Aerial Systems (UASs) or simply drones by many. UASs could be used either exclusively to perform fire-spotting at the GDS or in conjunction with manned aircraft. Some of the reasons for considering small UAS for GDS fire-spotting include the possibility of: 1) lower-cost operations, 2) shorter response times since multiple low-cost UAVs could be owned and operated by GDS personnel, 3) more frequent UAS operations, 4) improved fire-spotting capabilities given sensors built-in to the UAS vehicles, and 5) reduced risk for GDS personnel.

In order for a UAS fire-spotting option to be successful the overall system would have to provide clear and significant benefits compared to the current manned operations. Recent developments in low-cost UAS technologies, such as autopilots, cameras, datalinks, and other systems have provided the feasibility of such an application. However, in addition to the basic technologies required to have effective UAS fire-spotting efforts, operations in the National Airspace System (NAS) pose significant challenges. A research effort was undertaken as part of the NASA UAS in the NAS project to investigate these issues.

The objectives of the current effort were to: 1) Determine suitability and utility of low-cost Small Unmanned Aircraft Systems (sUAS) to detect nascent fires at GDS; 2) Identify and assess the necessary National Airspace System (NAS) integration issues; and 3) Provide information to GDS and the community on system requirements and concepts-of-operation (CONOPS) for conducting fire detection/support mission in the National Airspace and (4) Identify potential applications of intelligent autonomy that would enable or benefit this high-value mission. This report discusses the results of a feasibility study conducted by NASA that was sponsored by the UAS in the NAS Program. Recommendations for a fire-spotting UAS approach for the GDS, including a concept of operations (CONOPS), NAS operational and regulatory considerations, and results from initial flight testing are included herein.

The problem to be addressed is approached by considering two separate aspects of the overall objective system. One aspect focuses on the purely technical elements of the fire-spotting objectives. The other aspect involves integration into the NAS. Proceeding in this manner allows a clear and simple assessment of the known minimum technologies required to perform the mission and evaluates candidate sensors, data links, aircraft platforms, search areas, etc. Then the integration into the NAS provides a focused look at the evolving regulatory issues associated with real-world UAS operations.

The technical issues of fires-spotting at the GDS involve definition of the area of coverage, the resolution and capability of the sensors, mission requirements, and the operational environment (assuming sanitized airspace). The area of coverage includes all of the GDS which is depicted in Figure 3. This area is approximately 20 miles long by 10 miles wide which results in approximately 200 square miles. The actual required search area is somewhat smaller than 200 sq-mi due to the presence of Lake Drummond and also due to a small series of roads in the GDS that support limited ground-based fire spotting. For this report, the GDS is assumed to be 10 miles wide by 20 miles long. The GDS Fire Station location is also depicted in Figure 3. As can be seen from Figure 3, the UAS would need to operate as much as ~10 miles from the UAS operator if operations are assumed to be conducted from the GDS fire stations. Ten miles is significantly farther than can be accomplished within line of sight of the operator, which is generally considered less than 3 miles for airspace clearance visual observation purposes.

Figure 3- Google Earth image of the Great Dismal Swamp National Wildlife Refuge.

Initially, it was expected that a sensor suite which replicated the existing process of fire spotting would be appropriate. As such, two types of sensors were considered, simple electro-optic (E/O) color cameras and infra-red (IR) cameras. While current E/O cameras are relatively inexpensive, current IR cameras can range from $2500 to over $75,000 depending on size, resolution, sensitivity, and other factors. Selection of the least costly IR sensor that could still perform the fire-spotting mission adequately was anticipated to require testing of a variety of IR sensors to determine their suitability vs. cost.

Current manned fire-spotting efforts at the GDS employ the Bell B3 or L4 helicopters and Cessna 206 aircraft. A photograph of a Bell B3 helicopter is provided in Figure 4. The Bell B3 has a maximum speed of 120 kts (~138 mph) and can remain airborne for approximately 3 hours. A photograph of the Cessna 206 aircraft is provided in Figure 5 which can cruise at 142 kts (163 mph), has a stall speed of 54 kts (63 mph), and can remain airborne for approximately 5 hours. The GDS spends approximately $1,250/hr for helicopter flight time and $265/hr for the Cessna 206. One reason the Cessna 206 is much less expensive is that the GDS has access to a government-owned aircraft. Helicopter fire-spotting flights can employ the helicopter's higher-speeds to transit to areas of the GDS,

Figure 4 - Bell B3 helicopter.

Figure 5 - Cessna 206 aircraft.

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then slow-down and potentially hover to inspect specific areas. The Cessna 206 can achieve higher speeds than the helicopter, but can only slow-down to approximately 90 kts to inspect various areas of interest. GDS flight requirements require specially-trained personnel to conduct flight operations. These specially-trained personnel are sometimes not available and lead to delays in mission execution and/or increased overall costs. Presently, helicopter operations involve contracted helicopters based in Richmond, VA. In order to get one hour of fire-spotting over the GDS requires 3 hours of helicopter time, approximately (~3*$1,250=$3,750). Approximately one hour of flight time over the GDS is required to perform a single inspection.

Since "low cost" was identified as key to the success of any future small UAS system for this role, this guided the selection of both research platforms that were used as well as other subsystems such as the autonavigation or autopilot unit, the cameras, and the downlinks used. Further, the total cost of the research itself was, by necessity, limited, which further emphasized the low-cost aspects.

In addition to cost, there were several issues relating to initially unknown system requirements. These included whether real-time downlink of all the sensor video data was required, what data elements were required to geo-locate the fire, what is the practical endurance of a range of sUAS in this class for this mission, and what are the utility issues associated with various launch and recovery methods such as "runway" takeoff and landing, hand-launch, or V/TOL.

The previous discussion defined technical issues for a vehicle to support fire-spotting activities at the GDS. In real-world operations the UAS will need to integrate into a NAS that has evolved in support of manned aircraft. Manned aircraft operations vary widely in terms of communications, navigation, mission objectives, and vehicle separation assurance. Some manned aircraft operations, such as those conducted in Class-A airspace above 18,000 ft, have all aircraft under direct control of a human air-traffic control (ATC) specialist who provides vehicle separation. At the other end of the spectrum, aircraft operating in Class-G airspace, pilots are not required to communicate with ATC at all and are totally responsible for providing vehicle separation. This is referred to as "see and avoid" operations.

UAS aircraft do not have pilots onboard to perform "see and avoid" tasks and mitigate risks to the general public. As a result, the UAS CONOPS and systems need to include some other method(s) of the "see and avoid" function to operate within the NAS.

Figure 6 provides a portion of the Washington area FAA sectional chart depicting the airspace associated with the GDS and surrounding areas. The magenta shaded line cutting across the GDS from west to east at the Virginia/North Carolina border denotes Class-G airspace abutting Class-E airspace at 700 ft AGL. This results in the airspace directly over the GDS being Class-G to 700 AGL for portions within Virginia. The southern portion of the GDS is Class-G airspace up to 1,200 ft AGL with Class-E airspace above that.
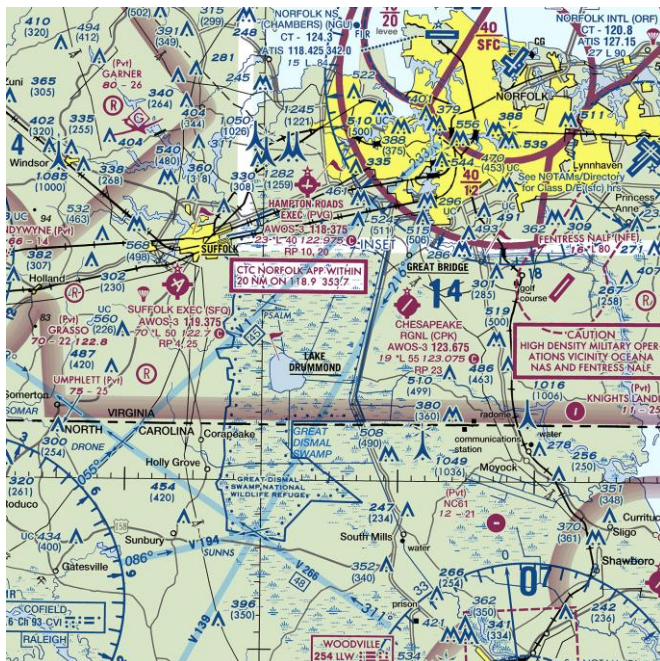
Figure 6 - FAA Sectional Chart excerpt for the GDS area.

III. Preliminary Research to Address Technical Issues and Challenges

To address the technical objectives of the research, it was determined that the effort needed to focus on a demonstration of a representative system or systems that would exhibit the expected characteristics of low cost and reasonable utility for fire spotting. It was unclear initially what capabilities either the platform or the sensors would need to be. However, it was assumed that the cost of the research to the project would also have to be minimized. With this in mind, the selection of both platform and sensor suite was, by necessity, limited to readily available (or acquirable) assets.

A. Research Platform Selection and Construction/Modification

When considering which platforms would be suitable for a demonstration of capability, four platforms were initially considered. These were: (a) the FireFlyer student built UAS, (b) a NASA-modified FQM-117B (MigLH), (c) a COTS hand-launched UAS (Bixler) and (d) a COTS multicopter (Y-6). Each of the salient characteristics is shown below.

1. FireFlyer

Figure 7 – FireFlyer sUAS

The FireFlyer UAS (Figure 7) was custom-designed and student-built in 2013 (with funding supplied by the UAS-in-the-NAS project and the Aeronautics Academy) specifically to address the GDS fire-spotting mission. Designed to have a 1-hour endurance, it carries a payload of both a forward looking color daylight camera and a down pointing IR camera, both fixed to the airframe. It was initially assumed that this airframe would provide the needed endurance and sensors to evaluate the fire-spotting utility of this class of vehicle. However, during some of the early flight testing for this effort, the airframe was heavily damaged. The cause was a hard landing that was determined to be due to a lack of control authority of the empennage shortly after takeoff. As a result, a significant effort would have been required to re-design and re-fit the aircraft with a new empennage for use in this research activity. It was determined that this would not be advantageous to achieving the project cost or schedule constraints.

2. MigLH

Figure 8 - NASA Modified FQM-117B, tail designator LH

The NASA-modified Army target drone, formerly designated as an FQM-117B (Figure 8) is a 1/9th scale Mig-27 foam aircraft that was selected for this effort to simply test the avionics in a relevant fire-searching environment at a minimum cost. Several Mig airframes were available at the start of the project that were leveraged for this effort. The Mig has a wingspan of 5'6" and an overall length of 6 ft. The design takeoff weight of the Mig as a target drone was specified at 8 lbs, but for the current effort the vehicle was operated at 15 lbs. Much of the increase in weight was due to the addition of a landing gear and electric propulsion system. Some of the benefits of the Mig included large internal payload volume and easily modifiable foam construction.

Initially, the MigLH was powered by an E-Flite Power 90 electric motor with a 16" propeller. During operational testing at the grass strip at the Military Aviation Museum the need for a higher takeoff thrust margin was discovered. Subsequent propulsion was provided by an E-Flite Power 160 outrunner style electric motor powered by a 10-cell 7800 mah battery pack. Overall, this propulsion system provided adequate thrust and approximately 15 minutes of flight time while maintaining a 20% battery reserve. Electric propulsion was beneficial for this effort since it produces a lower vibrational environment compared to reciprocating engines, and does not produce emissions that could form residues on the aircraft and compromise camera views. Electric propulsion is also considered likely for an actual fire-spotting aircraft due to environmental considerations at the refuge such as noise and emissions. Radio control (R/C) of the Mig was accomplished using a JR/Spectrum 12X transmitter and 1222X receiver. Once the aircraft was airborne and stabilized at the desired observation altitude, control was transferred to the autopilot using one of the switches on the 12X. As a result of its design as an inexpensive and rapidly-assembled target drone, the Mig's aerodynamics, high weight, and limited endurance of the vehicle and rendered it unsuitable as an actual fire-spotting aircraft. However, the Mig did meet all of the testing needs for this effort.

Additional NASA modifications from the bare airframe included the addition of a landing gear, rudder, fuselage reinforcement, and three payload bays. Details can be seen in Figure 9.
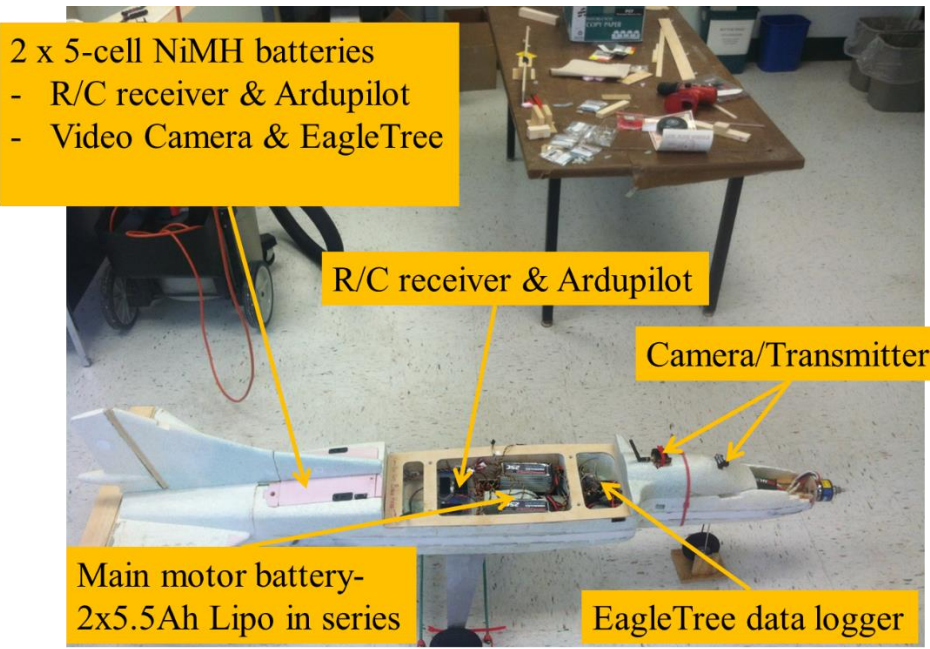
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Figure 9 - Interior of MigLH.

Figure 10 - Ardupilot 2.6.

In addition to an EagleTree data logger, an Ardupilot autonavigation unit was installed in the vehicle. The Ardupilot, shown in Figure 10, was chosen as a COTS autopilot representative of the type of low-cost unit an affordable UAS would likely have to use. The cost of the Ardupilot unit was less than $500. During the initial flight testing, this proved to be somewhat problematic for two reasons. First, the autonav unit itself is not "general purpose" in that it has several parameters which must be set properly, including PID gains, outer-loop control parameters, and others. Tuning these parameters required an inordinate amount of flight testing as there was no concise documentation on how to compute these parameters from known physical quantities. Second, the reliability of the compass and GPS sensors was less than optimal, and, in some cases, the apparent failure of these sensors was not readily detected by on-board diagnostic hardware and software. This greatly complicated the "tuning" process since it was unclear after a change whether the adverse response was due to the parameter being changed or the sensor failing. Eventually, a new version of the autopilot became available which provided an external, easily replaceable module containing both an upgraded GPS and more reliable compass module. This greatly improved the ability to tune the autopilot to the system. After dozens of flights oriented towards tuning with little progress, once the system was proven reliable, it took less than 6 flights to get the autopilot sufficiently tuned to perform the research flight tests and demonstration. Acceptable performance for this effort was defined as autopilot-like controlled flight over various test fires with aircraft attitude variations less than +/-10 degrees, altitude error less than +/-10 meters, airspeed error less than +/- 3 meters/second. Further adjustments to the autopilot parameters could have slightly improved the control of the aircraft, however, schedule constraints precluded additional autopilot tuning.

3. Bixler

The Bixler UAS, sold by 3-D Robotics and shown in Figure 11, is representative of the class of small, hand-launched vehicles that are currently available in the US market. It weighs approximately 3.5lb. and

Figure 11 - Bixler COTS sUAS.

has a wingspan of less than 5ft. It uses the Ardupilot autopilot similar to what was installed in MigLH. It is equipped with a color daylight camera and video overlay. Flight tests with this platform initially had the same reliability issues as the same unit in MigLH. Subsequent upgrade of the autonav unit provided much better reliability, similar to what was seen with the MigLH. It was felt that whereas the MigLH requires a "runway" for takeoff and landing, the Bixler had more utility since it required far less of an operating area for launch and recovery due to being hand-launched and belly landing recovery. Flight speeds were much lower for the Bixler than those of the MigLH.

4. Y-6

Figure 12 - 3D Robotics Y-6 V/TOL sUAS

The Y-6 (Figure 12) is a small (< 4lb) multi-copter sold by 3D Robotics. It has 6 motors mounted in a Y-shaped frame. The basic vehicle comes with a body-fixed color daylight camera with overlay data from the on-board autopilot unit. While this particular platform uses the more advanced Pixhawk autopilot from 3D Robotics, the initial autopilot unit suffered an IMU failure during its first flight. After replacement, no further autopilot issues were discovered. Replacement of two of the electronic speed controllers was required after the system developed a tendency to shut down one of the motors on one leg. After replacement, no further issues have been encountered.

5. Ground Control Station

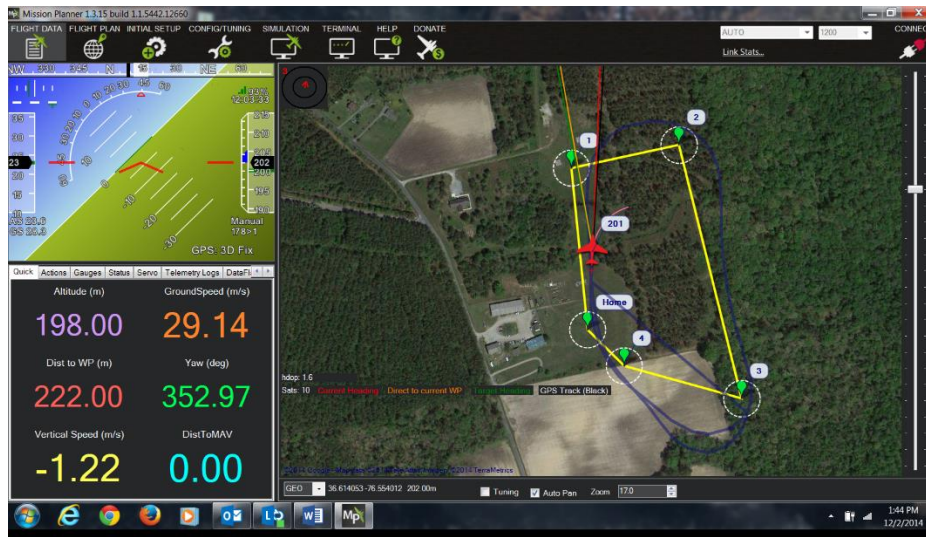The ground control station (GCS) used with all of the sUAS systems used was composed of several elements.

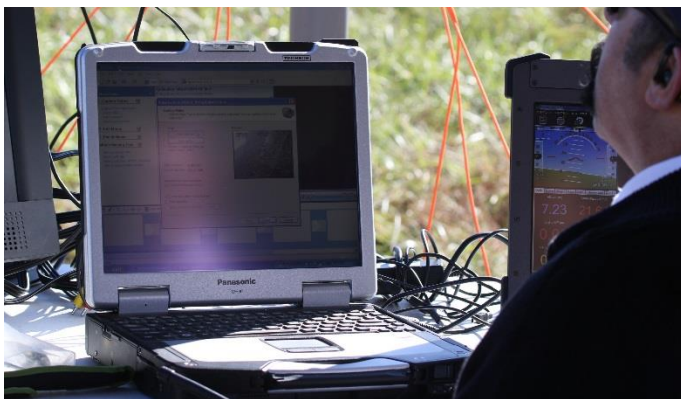Figure 13 - Image from the Mission Planner software.

Those elements were: 1) Autopilot Mission (APM) Planner software, 2) Autopilot datalink, 3) Autopilot laptop, 4) 4-G wireless hotspot, 5) Video monitoring/recording laptop, 5) Video datalink. The APM software was used to establish the desired waypoints for the vehicles to fly when under autopilot control. The APM software also supported autopilot parameter adjustments which could be performed at any time the datalink was established with the aircraft. A screen image from the Mission Planner is provided in Figure 13. In Figure 13, it can be seen that Heads-Up-Display (HUD)-like aircraft airspeed, altitude, and other parameters are provided in the upper left of the Mission Planner display. A gods-eye-view map, showing waypoints, desired route, and aircraft location are shown on the right in Figure 13. Quick-view parameters including altitude, ground-speed, distance to next waypoint, heading, vertical speed, and distance to the home point are provided in the lower left of the Mission Planner display. The autopilot laptop was a commercially available ruggedized unit running Windows 7. The 4-G wireless hotspot was required to support downloading of the terrain maps for the APM software. Pre-loading the terrain maps was also an option for the APM software. The video recording laptop was a standard computer running Windows XP. Its' function was to support configuration of the video telemetry system, monitoring the telemetered video during flight, and capturing and recording the video to the hard-drive for subsequent analysis. Figure 14 provides a photograph of video control portion of the ground station. The Autopilot datalink operated on the 900 mHz frequency band while the Video datalink operated on the 5.8 gHz band.

Figure 14 – Video control ground station.

B. Sensor Selection and Testing

The initial expectation was that smoke plumes would be readily visible against the horizon, particularly in wooded areas so the color daylight cameras in all three platforms were positioned to look directly forward. A low-cost 520 TV line color daylight camera was used to determine how well this type of sensor could detect smoke plumes. Initially, the camera was mounted on the top of the vehicle along the centerline, providing something similar to a "cockpit view".

Second, an infra-red camera was expected to be used to locate fire hot spots. Since the cost of IR sensors varies directly and substantially with the resolution (and to a lesser extent sensitivity), selection of the lowest performance sensor that would provide a reasonable likelihood of

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Figure 15 - PathFindIR camera from FLIR Systems.

detecting the hot spots would be preferable. However, the needed level of performance required was not known a priori. Initially, only a low-performance IR sensor was available, a 160x120 (interlaced to 320x240) resolution as shown in Figure 15. Acquisition of a 336x240 and 640x480 was initiated on the expectation that the additional resolution and sensitivity would be needed for the detection. The camera has a horizontal field of view (FOV) of 36 deg. Current cost of this type of low performance IR sensor is about $2500.

Both the E/O and IR cameras produced NTSC standard analog video outputs. These outputs were fed into a switching device which allowed the pilot to switch between the two sensors in flight. The single video stream was overlaid with some of the aircraft state data by using the EagleTree OSD system (Figure 16). The EagleTree sensor and data logging suite cost approximately $250.

Figure 16 - Eagle Tree OSD Pro unit.

In addition to the E/O and IR streamed video, a separate, toallt self-contained high-definition 720p video recorder was attached to the airframe to record up to 3 hours of digital video directly. This unit was oriented to point directly down from the airframe and had a 120deg. FOV lens. This unit was initially installed to merely document the flights and provide a situational awareness after the flight. This particular unit cost less than $40.

C. Fire Simulation Targets

In order to test the efficacy of the sensor suite and the platform to perform basic fire detection tasks, a series of flight tests were conducted using simulated targets of different types. First, a road flare was placed in a metal bucket and lit. This would represent an easy to implement, low cost method of providing a target with the hottest target temperature likely to be encountered (roughly 2000deg. F). Second, a fire pit approximately 3ft in diameter with indigenous organic material such as wood branches, leaves, pine needles and peat moss were used as representative of a "nascent" fire similar to what would be expected at GDS. Third, a typical steel grill was used with a charcoal fire and the lid closed to concentrate the plume and somewhat attenuate the temperature signature during the test. The fire pit and steel grill were implemented after the initial set of flights showed adequate detection of the road flare target. Figure 17 shows these three targets.
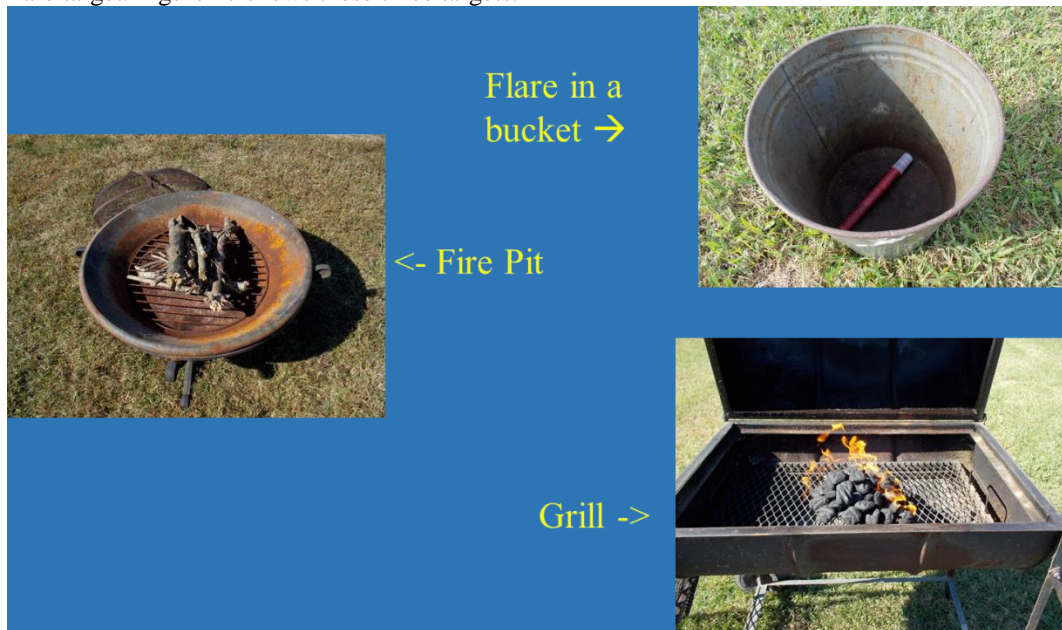

Figure 17 - Representative fire targets

D. Research Flight Tests and Results

Flight operations using the MigLH and Bixler platforms were conducted at several locations in support of this effort. Initial flights were conducted at Ft. A. P. Hill, Virginia followed by operations at Smithfield, VA (31VA), and Virginia Beach Airport, VA (42VA). These flights included vehicle/system integration and checkout including autopilot and video acquisition and telemetry development efforts for the Mig and Bixler aircraft. Operations at 31VA and 42VA were conducted in Class-G airspace utilizing NASA MOA with the FAA. Operations at FT A.P.

Hill were performed in restricted airspace. Airworthiness and system checkout flights for the Y-6 were conducted at Langley Research Center using a tether arrangement.

Once the basic airframes, sensors, and systems were tested to ensure their performance, a series of flight tests were conducted at the Virginia Military Museum in Virginia Beach to determine the ability of the system(s) to detect the simulated fire targets. The basic series consisted of flights at 100m (328ft), 150m (494ft), and 200m (656ft) altitudes at airspeeds of 18, 20, 23, and 25 m/sec (40,45,51, and 56mph respectively) for each of these altitudes. Note that the highest test altitude at 42VA and 31VA was limited to 700ft. (213m) which was the upper limit of the Class G airspace at these locations. The IR video showed the road flare distinctly even with its small size at lower altitudes and speeds. As the altitude and speed were raised, it became more difficult to detect in real time due to its small size and rapidity of crossing the video screen.

Both the fire pit and grill were clearly visible in the IR imagery. An example of this is shown in Figures 18 and 19. Note that at the higher altitude of 200m (656ft), both targets were visible simultaneously owing to the wider ground swath of the camera at the higher altitude. At an altitude of 200m (656ft), the camera could view a 124m (407ft) wide track on the ground. One pixel represented approximately 0.8m (2.6ft.) on the ground. Temperatures of the fire pit ranged from 300-700deg. F depending on where in the fire the temperature was measured. The temperature of the outside of the grill was considerably cooler and more uniform at 350-450deg. F.
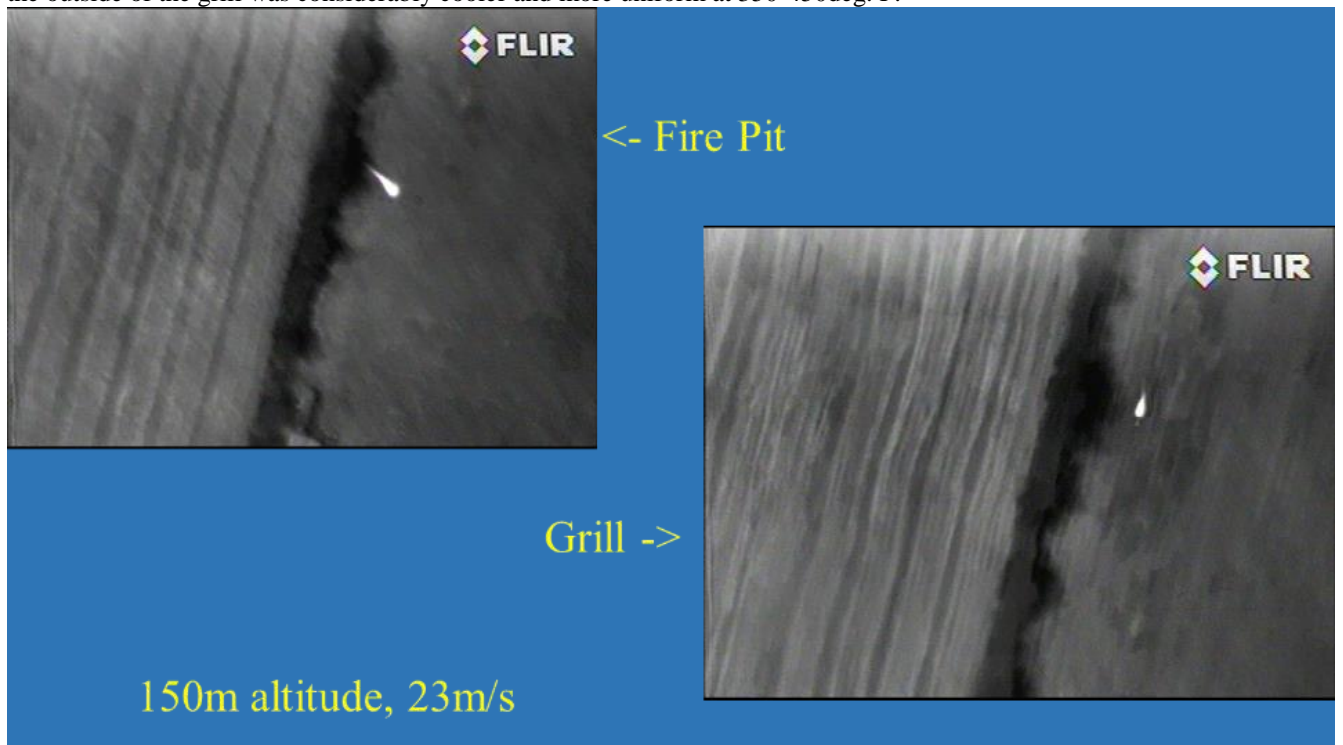

Figure 18 - IR image from video, 150m altitude, 23m/s airspeed

Figure 19 - IR still image from video, 200m altitude, 23m/s airspeed

During the flights, neither the MigLH nor the Bixler's color daylight camera provided video watchers with sufficient imagery to visually detect smoke plumes. It was later determined this was largely due to the use of very open space to place the targets and the subsequent rapid wind dissipation of the plumes. In addition, it was determined that the forward facing cameras on all platforms needed to have a more downward cant, and in the case of the MigLH be relocated to the bottom of the aircraft, to provide better plume imagery. Note that for the initial MigLH flights, much of the downward portion of the image was obscured by the airframe itself (see Figure 20). As a result, the forward facing camera was moved to the bottom of the airframe and re-installed at a 45deg. cant downward. Cameras on the Bixler and Y-6 were also canted down by 45 deg.

Figure 10 - MigLH forward facing camera image.

Also during the test flights, the system was demonstrated to have good link range for both video and autopilot telemetry to roughly a half mile from the GCS. In addition, an endurance of 15 minutes with a 20% battery capacity margin was demonstrated.

IV.   Results from GDS Flight Experiments

Once the systems were shown to be functioning reliably and appeared to be capable of detecting simulated target fires, a set of flights was conducted at the GDS itself. A set of 5 flights was conducted on November 19, 2014. Three of these flights were conducted using the MigLH platform and two with the Y-6 platform. Since the imagery provided by the MigLH proved effective, the Bixler airframe, which carried the same E/O camera was not used for these tests.

Two areas at the GDS were identified as possible operating locations for the MigLH "runway". The first, shown in Figure 21, is an open area near the GDS Fire Station. This had the advantage of being close to the actual end users, ie the Fire Management team at the GDS. Further, near the fire station itself is an area that is commonly used for training of fire teams. The second area was near Lake Drummond on an access road. This location had the disadvantage of the road being gravel and narrow, increasing the likelihood of damage to the airframe as well as limitations on the ability to set target fires.
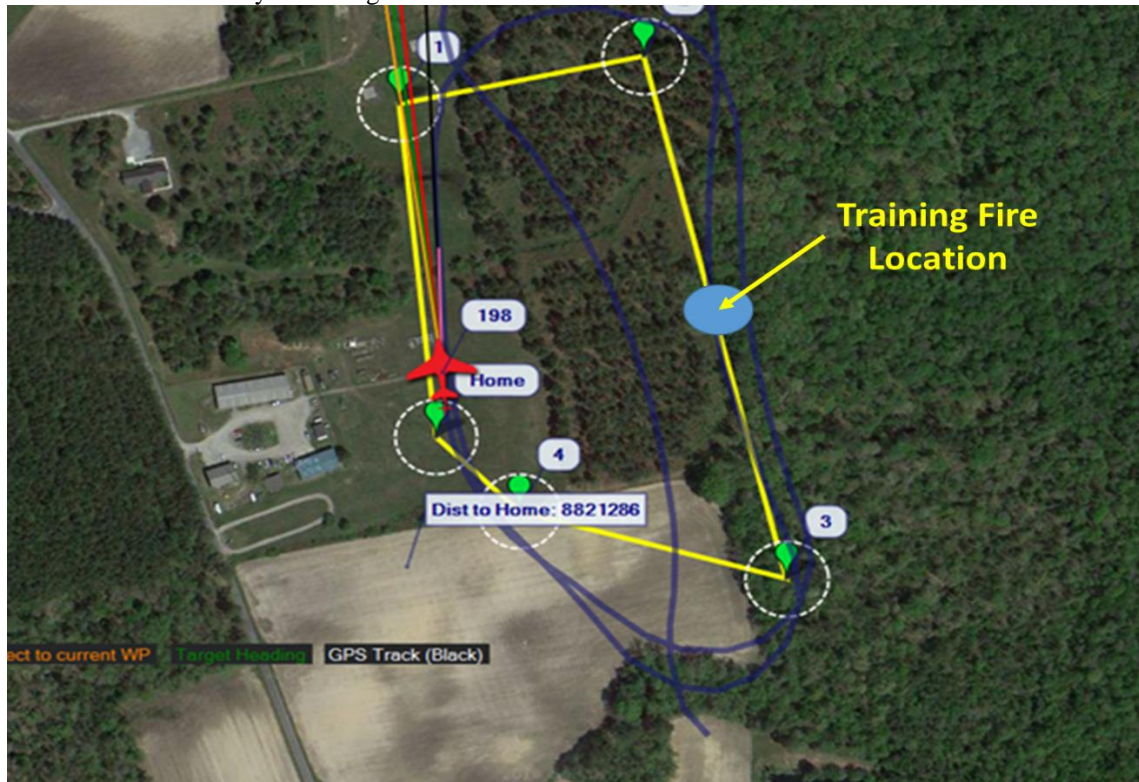

Figure 21 - Fire station operating location at GDS

For Flight #2, GDS personnel set a training fire at the base of a tree in the training area. This fire would be similar to what would be found after a lightning strike. Figure 22 shows the base-of-tree fire after it had been extinguished after the flight. The area around the base of the tree contained the types of indigenous materials normally found in the GDS that would act as fuel for the lightning.

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Figure 22 - Base of tree fire.

Figure 23 presents an example of the 45-deg look-down camera video showing the flight data overlay. Existing battery voltage (38.10v) and current draw (27.2 A) are displayed in the upper left of Figure 10. At the top of Figure 10 is the normal force in g-s (0.69) and the present Watt consumption (1127) of the aircraft. The amount of energy consumed by the flight in milli-amp-hours (mAh) (1094) and temperature of the engine batteries, TpA (42 deg F) is displayed in the upper right of Figure 23. Barometric altitude (260 m) is displayed in tape format in meters on the right of Figure 23. Current latitude (36.37' 0035") and longitude (76.33' 0272") are displayed in degrees, minutes, and seconds, in the upper data fields on the lower left and right of Figure 10, respectively. GPS location combined with aircraft altitude, attitude, and heading can be used to pinpoint fire locations on the ground. Below latitude and longitude are the GPS altitude (655 ft) on the left and GPS ground track, Cou (118 degrees) on the right. In the middle is an arrow indicating which direction to turn to fly back to the home location. On the lower left is indicated airspeed (50 mph), distance to the home location (1,521 ft) in the center, and GPS ground speed (59 mph) on the right. Also visible in

Figure 23 - Example of the 45-degreee Look Down camera video.

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Figure 23 is one of the smoke plumes from the fires created in support of the flight test effort.
During the same flight, the IR imagery showed the fire burning. With the 200m (656ft) altitude and ~25m/s (56mph) airspeed the fire hot spot was visible for several seconds. Figure 24 shows an example of a still image extracted from the video.
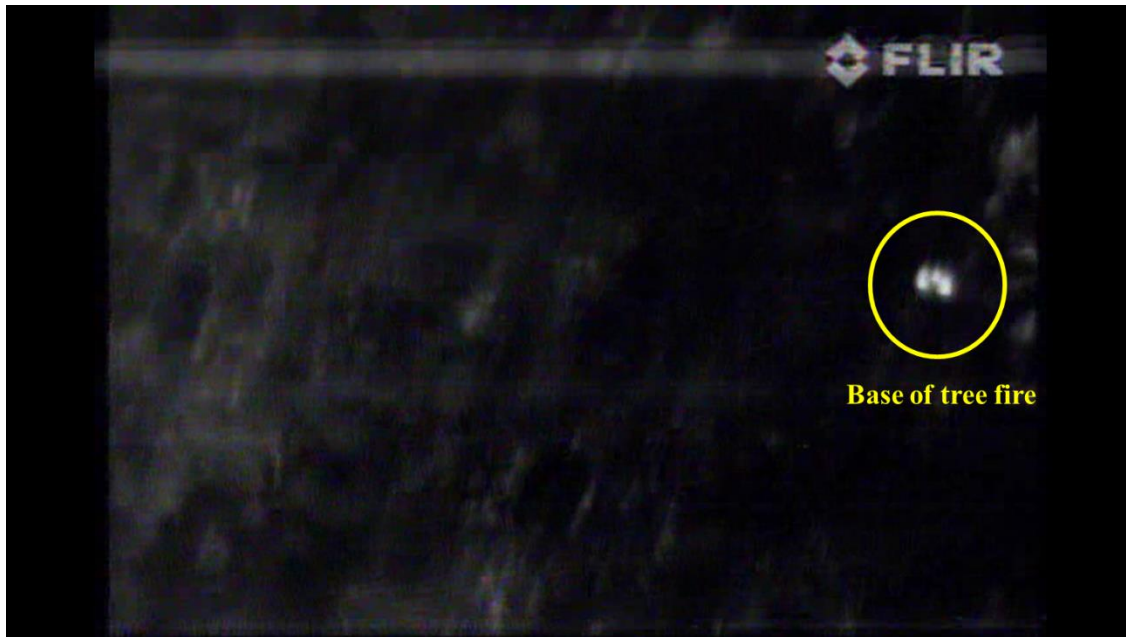

Figure 24 - Base of tree fire IR image.

The second flight of the MigLH platform flew over a training fire of a series of small ignition sources. IR imagery showed the multiple ignition sources clearly. In both flights, the 720p recorded video easily captured the smoke plumes from the test flights. Figure 25 gives an example of the recorded video.

Figure 25 - Smoke plume from training fire captured by 720p video camera.

Figures 26 and 27 provide photographs of the MigLH during operations at the Great Dismal Swamp Fire Station location. An approximately 550 ft long by 50 ft wide grass runway was mowed into a field behind the Great Dismal Swamp Fire Station. This resulted in a runway which was only somewhat rough. However, as part of the changes made during the initial research flights, larger tires had been installed on the landing gear providing better propeller ground clearance and rough field performance. Takeoff field length over a 10ft. obstacle was approximately 200ft, while landing over a 10ft. obstacle required approximately 500ft.

Figure 26 - MigLH during landing at the Great Dismal Swamp Fire Station.

Figure 27 - MigLH in flight at GDS.

The Y-6 was flown twice, once in manual mode, once in full auto mode where the vehicle took off, navigated through its mission waypoint set, and landed autonomously. Figure 28 shows the Y-6 in flight with Figure 29 an extract from the Y-6 video downlinked.

Figure 28 - Y6 V-TOL UAS in flight at GDS.

Figure 29 - Imagery from Y-6 at GDS.

V.   Mission Analysis for future sUAS Fire Spotting

One of the primary design variables to be considered for the GDS fire spotting mission is system endurance required, and relatedly, speed and altitude for the mission. Therefore, an analysis was conducted to investigate the impacts of elements such as altitude available, vehicle speed, and sensor FOV to the time required to image the entire GDS. The analysis assumed the entire GDS would be searched in a simple stacked-row pattern, with turn time between rows ignored.

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For this analysis, altitudes of 400, 700, 1200, and 2000 feet were evaluated. These altitudes correspond to the lowest, most restrictive, maximum altitude for UAS operations (400 ft, 122m), the upper limit of Class-G airspace over the northern portion of the GDS (700 ft, 213m), the upper limit of Class-G airspace of the southern portion of the GDS (1,200ft, 366m), and the altitude that GA aircraft need to stay at or above while flying over the GDS (2,000ft, 610m) because of its status as a National Wildlife Refuge. Figure 30 illustrates the scan width for combinations of altitudes (400, 700, 1200, and 2000) and scan angles (60, 90, 120) for a downward-looking camera. Note in Figure 31 that the labels for the abscissa are concatenations of the scan altitude and scan angle. The results are sorted from lowest to greatest. From Figure 30, it can be seen that the effective scan widths range from as low as approximately 500 feet for the 400 ft scan altitude with 60 deg scan angle up to almost 7,000 ft for the 2,000 ft scan altitude with 120 scan angle. It can also be seen in Figure 31 that results were similar for different combinations of altitude and scan angle. For example, the results for the 700 ft and 120 deg scan angle were nearly the same as the 1,200 ft, 90 deg, and 2,000 ft, 60 deg combinations. While the similar scan widths can be achieved for these three combinations of scan altitude and scan angle, the primary difference would be the size of the camera pixel on the ground. Higher resolution cameras would likely be needed for higher altitude fire-spotting. Figure 32 illustrates the time required to scan the GDS for the series of altitudes and sensor scan angles described above for speeds from as slow as 20 mph up to 120 mph. The time required to perform the 180 deg turn to start the next scan is not included. The resulting time only indicates actual flight time and does include pre-flight or other preparation time. What can be seen from Figure 32 is that the 400ft scanning altitude meets an assumed 8-hr requirement only for scan angles of 120 degrees and speeds greater than ~95 mph. This speed may not be achievable for a low-cost UAS. Results for the 700 ft scanning altitude are better with both the 90- and 120-degree scan angles being feasible. Speeds as slow as ~55 mph could scan the entire GDS with a 120 deg HFOV at 700 ft. Increasing the scan altitude to 1,200 and increasing the scan angle to 120 degrees would be required to enable slower, more efficient, scan speeds of ~35 mph. The 2,000 ft scanning altitude would enable use of narrow field of view cameras and/or slower scanning speeds.
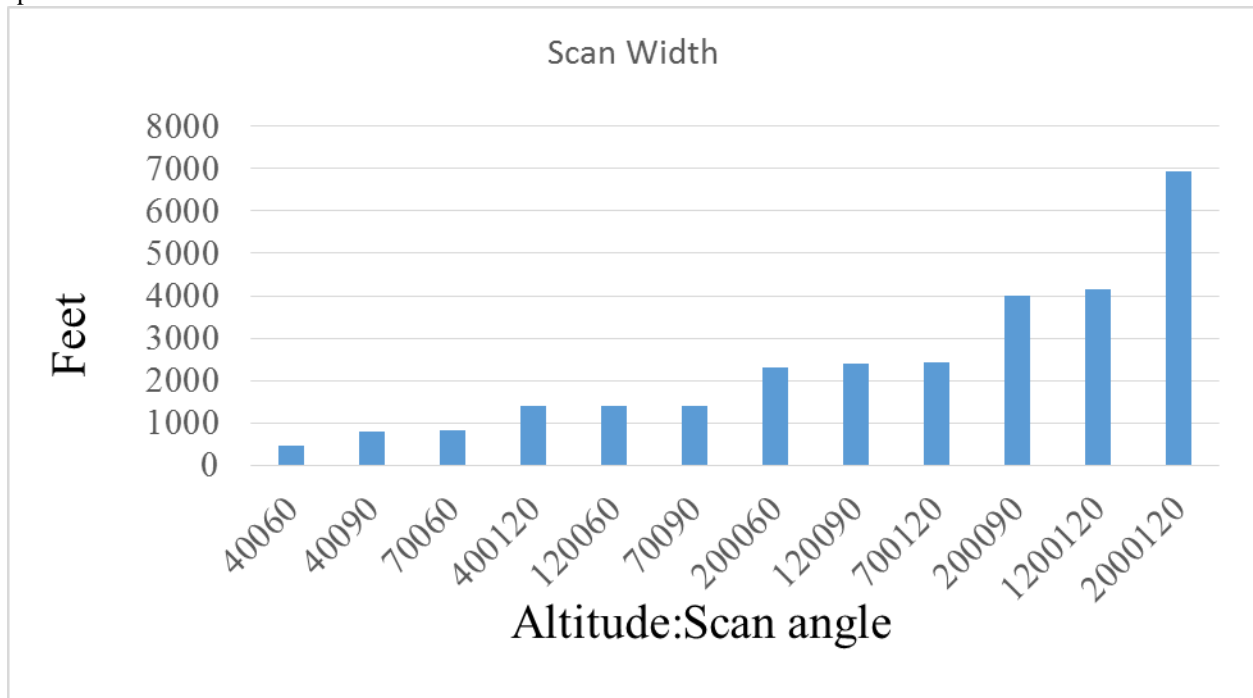

Figure 30 Ground scan width for a combination of altitude and sensor FOV.
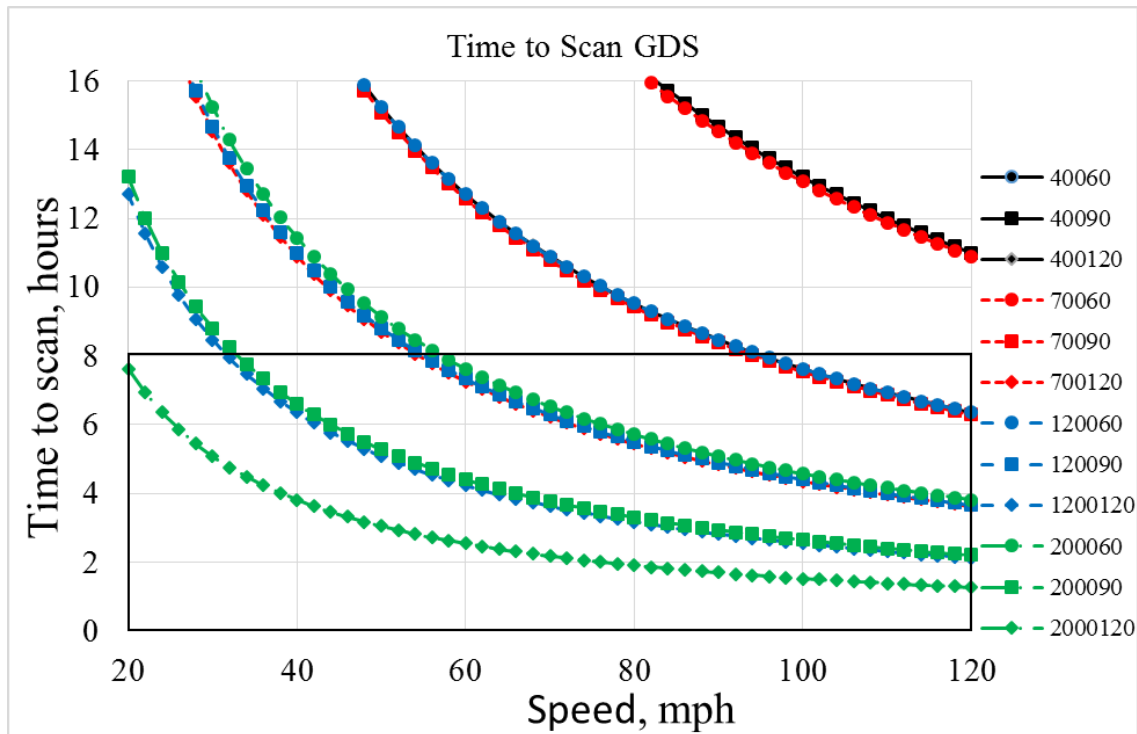
Figure 31 – Estimated Time to Scan the GDS

The previous analysis assumed a "lawn mower" pattern which traverses the entire GDS. An initial attempt was made to develop an optimized route to survey the lightning-strike locations using a genetic algorithm. In the figure below, the 617 lightning strike locations from Figure 2 that were within the GDS were referenced to the south-west corner of the GDS. Distances were measured in kilometers for this initial route optimization effort. The lightning strike data was partially sorted as a result of previous route optimization effort which is the reason for the color patterns in the distance matrix. Distances between lightning strikes ranged from a few meters up to greater than 30 km. For this solution the genetic algorithm population size was set to 2,000 and a total of 50,000 iterations were performed which took 2 hours to run on a standard laptop PC. The genetic algorithm solved the traveling salesman problem and created a route that was 419 km (260 mi) long. The result of this is that a UAS would require to fly at a speed of ~33 mph to fly to all of the 617 lightning strikes in 8 hours of flight time or 43 mph for 6 hours. This is significant in that if airspace integration requires the UAS to fly at low altitudes (i.e. 400 ft), then searching the swamp in an organized lawn-mower pattern would be time and/or speed prohibitive as indicated in Figure 31. If it can be assumed that the nascent fires are only at the lightning strike locations, the GDS could be scanned for fires by overflying all of the lightning strike locations. Operations at lower altitudes could also provide some improved capabilities due to the ability to operate when cloud ceilings were lower than required for manned operations. The lightning strike activity used for this analysis was provided by GDS personnel and it is unclear if this is indicative of low, average, or an extremely-high amount of lightning strikes. This analysis points towards one possible future application of intelligent autonomy – reducing the required endurance (and subsequent expense) of the system required to scan the GDS.
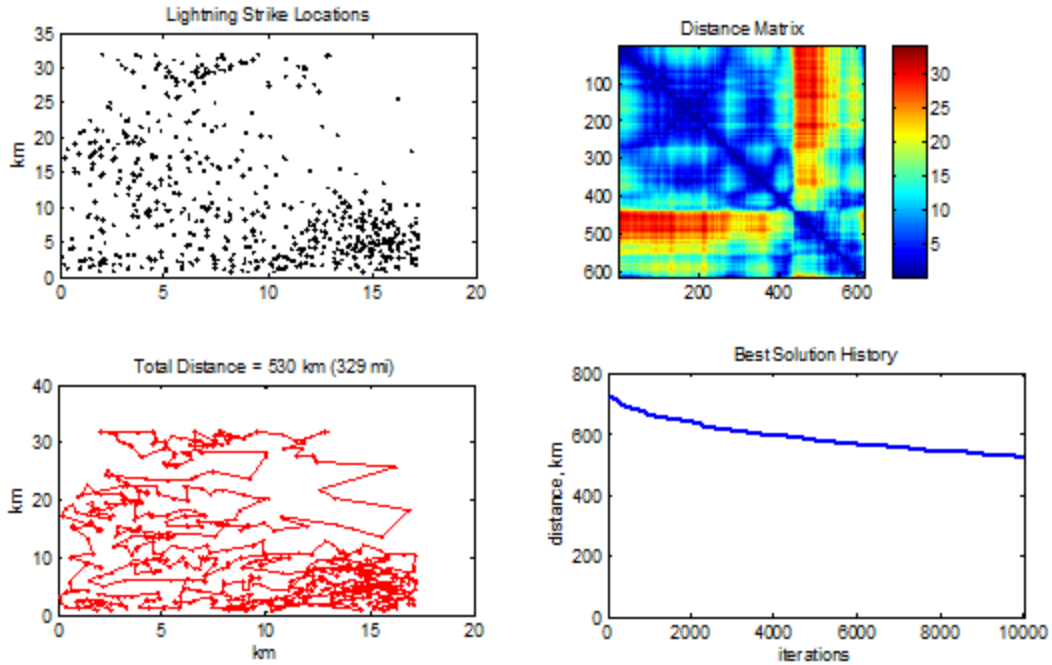
Figure 22 - Genetic Algorithm Reduction in Search Time.

Another analysis that is instructive is one dealing with geo-location of the fire using the data and imagery acquired. Establishing a baseline error in the location will provide a basis upon which a future system requirement can be based. Figure 33 shows the basic position error analysis. Using a body-fixed camera limits the accuracy of the geo-location. The GPS system in flight often has a horizontal dilution of position of approximately 1m (3ft.). Similarly, the error in the altimeter measurement is roughly +/- 1m (+/-3ft).
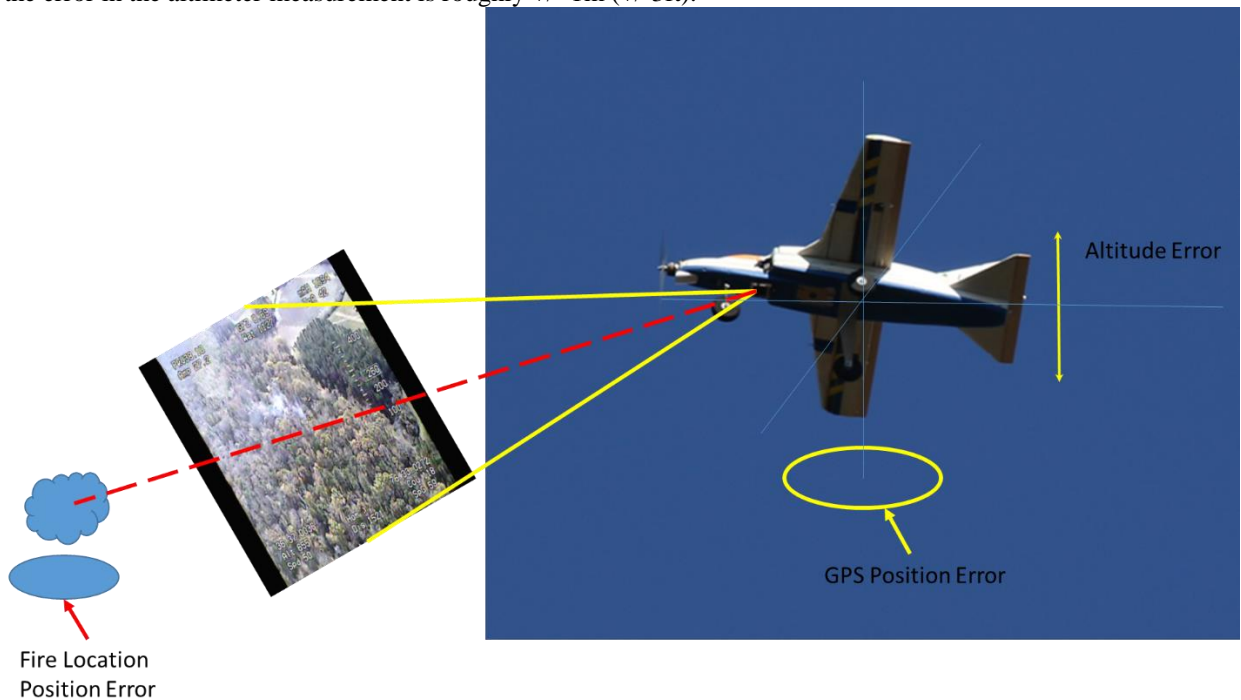

Figure 33 - Fire Location Error diagram.

At an altitude of 700ft., the ground position error, assuming no pitch, roll, or yaw angles would be +/- 3.5ft. However, in flight, the roll, pitch and yaw variability can exceed 2deg, further adding as much as 50m (164ft) to the potential fire location position error. If the aircraft's "pose" data from the on-board inertial measurement unit (IMU) can also be incorporated and synchronized with the image data, then the error gets reduced back to simply the GPS error and altitude measurement error and the accuracy of the IMU data. Another clear possibility is to consider the use of 3-axis stabilized gimbaled sensors, which would eliminate the need for frame-accurate synchronization of the video with the autopilot IMU data but with the incurred size, weight, drag, cost, and complexity of the gimbal unit considered as part of the design space.

VI.   Recommended Requirements for Fire Spotting sUAS

General requirements for a future system can be extracted from the results of the efforts to date and the lessons learned. A partial set of these recommended requirements and rationale are listed below:

1.0   The UAS design should be an order of magnitude less expensive than corresponding manned aircraft to provide fire spotting.
In order to implement a UAS Fire-Spotting system, it has to be able to provide the same, or better, level of performance while costing less.
Order of magnitude cost differences would help to ensure a resulting more cost effective system after unanticipated UAS costs are realized later in the design.

2.0   The UAS should be operable by GDS personnel with limited training.
In order to meet requirement #1, the UAS should be operated by existing GDS personnel in order to minimize costs.
Training to operate the UAS would be considered to be no more than one to two person-weeks.

3.0   The UAS should be operable from existing GDS property.
Significant investments in runways, for example, could lead to increased costs and make meeting requirement #1 impossible.
Because of the nature of the refuge, there is limited access to the majority of the property along with a significant lack of "open" space for runways.

4.0   The UAS should provide real-time imagery to the ground station operator.
Timely viewing of at least a portion of the imagery is considered essential for effective fire-spotting.

5.0   Imagery should also be stored on the UAS for subsequent post-fight retrieval.
Storing video imagery onboard the aircraft provides a source of imagery without potential data link degradation which can be subsequently viewed in detail post-flight.
On-board storage also provides a backup of the telemetered imagery.

6.0   The UAS should provide imagery sufficient to identify nascent fires of interest.
Fires with potential to grow into wild-fires need to be identified.

7.0   The mission availability of the UAS should meet or exceed, that of manned aircraft.
Manned aircraft are considered highly-reliable, yet not exclusively available due to the shared nature of the assets to minimize cost.
UAS are considered highly available, due to their on-demand nature.
Highly unreliable UAS would result in an ineffective system primarily due to its availability being poor.
Overall, the combined reliability/availability needs to be compared.

8.0   The UAS should provide response times at the same order of magnitude as manned aircraft or less.
Manned aircraft can provide a large area of coverage in a relatively short period of time. However, their "starting point" may be several days from when the demand arises.
Response times which are much slower, such as multiple days needed to scan the swamp, could degrade the UAS fire-spotting effectiveness.
This requirement will likely shape the UAS performance required.
Crew-duty limits, aircraft speed, endurance, range should be used to estimate the manned aircraft's performance for comparison purposes.
In addition, some consideration should be given to compare the reliability of the fire spotting itself between the two methods.

   9.0 The system should have an endurance and speed capable of searching the GDS in a single daylight shift (8-10hrs).

The sUAS should be able to provide more timely searches than is normally achieved with manned aircraft, which can sometimes take from 1-5 days to become available for fire spotting.

In analyzing mission requirements and considering the utility assessment, there are design trades which can be explored between speed and endurance for the mission, how many actual platforms are used as part of a "system", sensor fields-of-view, and others. As a threshold value, it would appear that an endurance of at least one hour should be expected as a minimum. An objective capability would extend that endurance to 3 hours. Speeds for scanning the swamp can be variable, however, a minimum of 40mph should be considered. A maximum of 60mph should be considered if the system is designed around manual observation of real-time video imagery to do the fire detection. If a system uses intelligent autonomy to do the fire detection, then the speed can be increased or decreased to whatever optimum speed is desirable for that system. In the future, technologies such as fuel cells may become ubiquitous enough (and inexpensive enough) to be considered for this application. In such an instance, it is conceivable that the entire GDS could be searched in a single flight. In addition, one consideration should be missions where scanning the entire GDS would not be necessary. Under those missions, transiting to the area of interest should occur at a reasonably fast pace to minimize personnel time.

10.0   Ideally, the system should require little launch and recovery open area.

Much of the GDS is forested with little open area, save that which was burned in previous fires. While launch and recovery from the fire station using a grass strip can be used, as was demonstrated, the ability to either hand launch or V/TOL would provide more options for launch and recovery elsewhere in the GDS.

11.0   The system should cost no more than $10,000 to acquire and should plan on a 3-5 year replacement cycle.

In the utility assessment, the $10k target appeared to be a breakpoint where potential users felt was "affordable". In terms of life-cycle, it is likely this class of vehicle will have no more than a 5 year useful life before the system is either worn out or obsolete.

A single GDS scan using a manned helicopter can cost as much as $4000.

The useful life of the airframe and associated systems in terms of hours of operation is somewhat dependent upon the endurance of the vehicle(s). For comparison purposes, a GDS scan rate of 10 per year can be used.

12.0   The system should be capable of operating at ranges exceeding 10 miles from the launch and recovery point.

While current operations are limited to visual line-of-sight, generally considered to be no more than 3 miles from the closest observer, future rules may allow systems to operate beyond line-of-sight. While some current beyond visual range of the launch point operations can be done using "daisy chained" observers such that the observers have line-of-sight to the sUAS and are in communication with the pilot or GCS operator, implementation of this approach would be problematic, owing to the inaccessibility of large portions of the refuge. That being the case, ensuring both the command and control link as well as video data downlink both operate well at these extended ranges is critical.

13.0   The system should have two independent means of control.

The system needs to be robust in the face of component or subsystem failure. Experience has shown that many of the low-cost autonavigation units and telemetry links can have undetected failures. In addition, if a command and control link is lost, there must be a secondary method of: (a) controlling the flight path of the vehicle directly, (b) a redundant command and control link replacing the primary, or (c) an on-board flight termination system which would land the sUAS in a safe and controlled manner.

14.0   The system should have a significant level of automation in the near term, autonomy in the far term.

As was stated in requirement #2, the users of the system will not be aviators and as such needs to perform basic flight in an automated fashion. It is expected that an autopilot unit will be an integral part of any future system. Features which would provide greater utility to GDS personnel would include: (a) autonomous takeoff and landing, (b) automated navigation to specific GPS waypoints, (c) ability to re-task the sUAS in flight to either new waypoints or to perform some type of "closer look" maneuver (which could be "stop and hover" for a V/TOL capable system or an "orbit around this point" for a fixed-wing system), (d) in the event of a problem with links, the system should be capable of auto-navigating back to some pre-programmed "safe ditch" location, and other similar capabilities.

In the far-term, the system will need to have sufficient computational horsepower to be able to process various types of intelligent autonomy algorithms in real-time on-board the aircraft. In the intermediate term, performing some of these tasks at the ground station may be a segue to on-board

In addition to the general requirements listed previously, several specific GDS fire-spotting requirements can be detailed based on experience gained during this research. These include:

1.0 The fire spotting utility of the system would be greatly enhanced by the use of a 3-axis stabilized gimbal to hold the sensors. The ability to modify the direction the sensors are pointing in real-time from the GCS is also desirable.

2.0 The system should be electric powered with rechargeable batteries to minimize the noise, cost, and environmental impact of GDS operations.

3.0 A method of viewing the real-time video in bright sunlight conditions is necessary for "manual" fire spotting with downlinked video. Further, a reasonably large video display screen appears to facilitate this detection.

4.0 While analog video downlink was sufficient for the experiments performed, a better capability would include higher definition digital video. However, this high-bandwidth application would currently require a digital downlink that far exceeds the cost limitations being recommended. As technology improves and becomes less costly, this capability should be revisited. In the interim, downlink of analog video in real-time and storage of higher resolution digital video on-board for later download would suffice.

5.0 The system should be able to operate in at least 80% of the weather environments normally encountered at the GDS. This would include operations in wind conditions up to 20kts, operations where ceilings are below manned aircraft operational limits, light precipitation (the system would not necessarily need to be completely waterproof since heavy rains or thunderstorms would likely preclude its use).

6.0 The cost to operate and maintain a near-term system should be less than $100 per flight hour.

VII.   Barriers to Far-term Vision for Fire Spotting sUAS

There are several barriers to the realization of the far-term vision, some technical, some regulatory, and some which are a combination of both. These key barriers are discussed below.

Barrier #1: There is currently no "acceptable" system for small UAS that can perform the see-and-avoid function for beyond line-of-sight operations.

a. It is likely that any such sense-and-avoid system will likely have to be a multi-layered approach, meaning, that no one "silver bullet" will suffice.

b. It is likely that ADS-B will be a requirement for future sUAS systems as part of, but not the entirety of, an SAA system.

c. There are a variety of potential technological solutions, all of which would need to be investigated as to their efficacy in the SAA function. These include high-resolution manual video scanning, high-resolution autonomous video scanning, LIDAR, radar, GBSAA, and others, each of which have very different cost and system design impacts.

Barrier #2: There is currently no applicable regulatory framework for beyond-line-of-sight operations of sUAS.

a. There have been operations conducted beyond line-of-sight be small UAS in the past. However, these operations have been by exception only and under very controlled circumstances.

b. Before the FAA can issue regulatory rules for BVLOS operation of sUAS, sufficient data will need to be acquired to provide the FAA with a reasonable certainty about the safety of these types of operations. This data requirement would include both reliability of the hardware and accuracy of detection and avoidance of manned aircraft as well as overall system-level data to support specific safety case analyses.

c. In collaboration with industry and the FAA, NASA can provide significant expertise, operational data, analyses, and recommendations for best practices for this regulatory framework..

Barrier #3: There is currently no autonomy architecture, including hardware and software architectures, that is suitable for providing intelligent autonomy to either the operation of the sUAS or the fire-spotting mission in particular.

a. There are numerous organizations that have been conducting research into intelligent agent behaviors and other elements which could be used to provide an intelligent autonomy capability. However, there is no over-arching system that would be amenable to an sUAS implementation.

b. The computational hardware requirements of today's intelligent autonomy exceed the size, weight, and power available in today's sUAS. A robust, miniaturized capability for autonomy implementation needs to be investigated.

Barrier #4: There is a lack of affordable solutions to this mission.

a. Many of today's systems were originally designed for military intelligence, surveillance, and reconnaissance (ISR) missions using high-performance sensors, systems, and airframes. These are unaffordable for this class of mission

b. Technologies applicable to this mission are rapidly evolving. Camera and sensor technology is improving and becoming less costly. New rapid prototyping methods are being developed. Low-cost "commodity" autopilot units are steadily improving. However, there are no methods or tools for "integrating" these into a solution set for an affordable fire-spotting capability.

VIII.   Conclusions

This effort achieved all four of the technical objectives envisioned for the research. Technical challenges were identified and researched to provide data to NASA and the GDS. Flight experiments were conducted in-situ at the Great Dismal Swamp over actual fires created specifically to mimic those of interest to the GDS. A number of analyses were conducted leading to a set of recommendations and identification of technical barriers to efficient utilization of sUAS for the GDS fire-spotting mission. Specific areas of intelligent autonomy were identified showing high-payoff application potential.

Findings from this effort indicate that low-cost UAS can potentially provide equivalent fire-spotting capabilities for a cost an order-of-magnitude less than existing manned aircraft. Results from the supporting flight testing confirm that low-cost (and low-resolution) IR cameras can effectively identify representative fires from altitudes as high as 200 m (656 ft). Results also indicate that high-definition downward-looking cameras and 45-deg downward/forward-looking cameras can be very effective towards spotting smoke plumes associated with fires in the GDS. Analyses conducted included data on accuracy of geo-location of fire positions which revealed that even a simple system can locate fires to within 150ft. Potential mission system design trade data was generated related to operational altitudes, speeds, and sensor fields-of-view. Finally, a set of recommendations to be used by NASA and the small UAS community identifying recommended system requirements, near and far-term concepts of operations were generated.

A set of key barriers to the realization of the GDS fire-spotting mission was identified. These include a lack of a sense-and-avoid system, the lack of a regulatory framework for beyond line-of-sight operations, the lack of an autonomy architecture, and the lack of affordability. In general, the inability to operate beyond line-of-sight renders the GDS fire-spotting mission unachievable.

The application of intelligent autonomy would have a dramatic impact on the GDS fire-spotting mission, including the fundamental feasibility of the mission itself. High-payoff applications of intelligent autonomy include: sense and avoid, autonomous fire detection, intelligent mission planning, robust intelligent flight control, and intelligent health monitoring and response.

Overall, the effort was found by the GDS to be of great value in learning what types of systems are available, what the requirements for a future system might be, and providing a glimpse of what future technology might hold to improve and enhance their capabilities. The NASA team obtained a great deal of practical data and insight into the limitations of today's low-cost sUAS systems and the regulatory limitations as they apply to a real-world mission such as the GDS fire-spotting, a clear mission for sUAS that is in the public interest.

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