Wildfire Identification Via CMOS Sensor Fitted High-Altitude Long Endurance (HALE) System

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Wildfires cause millions of dollars of damage each year and affect countless lives and habitats. Because of this, wildfire monitoring techniques have become necessary to protect property and natural ecosystems. Advances in Unmanned Aircraft Systems (UAS) have allowed for safer, more cost-effective monitoring systems of forest fires. A constellation of high-altitude long-endurance (HALE) fixed-wing aircraft, such as the Airbus Zephyr S, with a camera system designed to detect forest fires, could be used to monitor high-risk wildfire areas constantly. The challenges of wildfire surveillance, such as aircraft type, altitude, search patterns, number of aircraft, and wind speed are reviewed to create a concept of operations for using a HALE UAS to detect wildfires. Additionally, a camera system capable of detecting wavelengths of light emitted by burning potassium in plant matter will be analyzed as a possible solution to current multispectral sensor system challenges when attempting to detect wildfire sources. A proof of concept of this system has been designed. Likewise, an apparatus designed to test a prototype version of this camera system has been created.

I. Nomenclature

AR	=	Horizontal Pixels
FL	=	Focal Length
R	=	Altitude
SS	=	Array Width
W	=	Total Ground Field Of View Width
w	=	Pixel Ground Field Of View

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II. Introduction

Wildfires cause millions of dollars in damage and affect countless lives and habitats every year. In 2022, 68,988 wildfires in the United States burned over 7.5 million acres (3.03 million hectare) of land [1]. This is the highest number of wildfires in a single year in over a decade for the United States [1].

Thorough monitoring of high-risk areas and early detection can mitigate damage caused by wildfires, but each method of surveillance has a variety of challenges. Aerial vehicles such as low altitude Unmanned Aircraft Systems (UAS), spotter planes, and helicopters can only cover a limited amount of area (at infrequent intervals) due to constant refueling needs [2]. Satellites, on the other hand, can cover large areas with little-to-no maintenance, but their substantial distance from Earth's surface combined with very brief time-over-target ratios means that fires need to be thoroughly established before the satellite's camera is able to detect them [2]. In comparison, a system of high-altitude long-endurance (HALE) aircraft would be able to consistently cover a wide area for months at a time without having to refuel. Also, since these HALE aircraft would be closer to the ground than a satellite, it would be possible to detect fires in their early stages before they are allowed to grow.

In addition to the limitations of the vehicles responsible for wildfire surveillance, current camera systems struggle to detect the sources of fires. Sizable amounts of hot smoke in effected areas limit the capabilities of both infrared and standard cameras [2]. However, when plant matter burns, the potassium in the afflicted foliage emits specific wavelengths of light. If a camera could be designed to detect these wavelengths, it would be possible to view only the burning areas of a wildfire zone.

III. Objectives

The objective for this project is to design a high-level, aerial, wildfire detection system capable of early fire detection in addition to effective constant monitoring of high-risk areas. Specifically, a study needs to be performed regarding HALE aircraft to determine the most efficient vehicle for surveillance. Once the vehicle has been selected, factors such as area covered, field of view, altitude, number of vehicles, and search patterns need to be reviewed in order to diagnose optimal wildfire detection conditions.

In addition to developing a concept of operations for a HALE, a camera capable of detecting burning foliage needs to be developed for aerial usage. When the potassium found in foliage burns, it gives off a wavelength of light at 770 nm [3]. Therefore, a lens capable of filtering out all light outside of a narrow 770 nm – 780 nm band can be used to detect forest fires [3]. The entire camera system and its batteries will need to be fit into a box roughly the size of a 6U cube satellite in order to be a manageable size and weight for use in a HALE system.

IV. Discussion

A. Aircraft Selection

Since aircraft capabilities would determine many of the key factors regarding the overall surveillance system, the first step in this project was to decide which HALE vehicle would be most appropriate for the given mission parameters. The options ranged from high-altitude weather balloons to fixed-wing aircraft. For the aircraft to be selected for the mission it needed to be capable of meeting two major requirements. The first requirement was that the aircraft needed to be capable of reaching high altitudes for maximum ground observation, and the second requirement was that the vehicle would need to be able to stay aloft for as long as possible to ensure constant monitoring of high-risk areas.

There were several challenges when attempting to choose a specific aircraft. The aircraft needed to be able to fly above controlled airspace – at altitudes greater than 60,000 ft above the continental U.S. [4]. In order to do this, the aircraft needed to be lightweight to maximize efficiency but also be robust and reliable enough to survive many flight cycles, staying powered for months at a time, and also any potential strong wind gusts that may occur during climb or cruise. Many of the aircraft researched used high-density solid hydrogen for power; however, solar powered vehicles allowed for maximum endurance at the altitudes being considered. Another complication was that many HALE vehicles researched are still in the prototype stage. This makes it difficult to obtain specific data involving their capabilities. For example, aircraft such as the HELIPLAT claimed to be able to sustain high-altitude long-endurance flight but are conceptual projects and are not yet proven [5].

A constellation of fixed-wing aircraft was determined to be more effective for the mission than high-altitude balloons. While balloons would be easier to get to altitude and would require less overall power, fixed-wing aircraft have the advantage of maneuverability. High-altitude balloons and their limitations would require a greater number of vehicles to have the same frequency of visual contact that fixed-wing aircraft provide.

Eventually, the Airbus Zephyr S, as seen in Fig. 1, was chosen to be the aircraft the system would be modeled around. The Zephyr S recently demonstrated flight at a height range of 60,000 to 70,000 ft (18.3 to 21.3 km) for 64 consecutive days in the summer of 2022 [6]. The Zephyr has a wingspan of 82 ft (25 m) and a weight of around 166 lbf (75 kgf), making it extremely light for its overall size [6]. In addition to the airframe's weight, the Zephyr S can also carry up to 11 lbf (5 kgf) in payload weight, over double the estimated 5 lbf (2.25 kgf) of the proposed system [7]. The vehicle has a substantial amount of real-world data from experiments and successful flights and uses a system of solar powered arrays along its wings to maintain constant flight. Also, with an expected solar battery efficiency improvement of at least 10% over the next decade, it is possible an aircraft modeled around the Zephyr series would be capable of an even smaller and lighter airframe by the time the projected wildfire surveillance system would be ready for operation[6].

Fig. 1 An Airbus Zephyr HALE vehicle in flight [8].

B. System Design

The ideal altitude for the HALE vehicle would be 75,000 ft (22.9 km) for various reasons. Primarily, this altitude is above FAA regulated airspace, meaning there would be minimal air traffic [4]. Since the HALE vehicle will be flying for months at a time, it is a significant benefit to be away from air traffic and disturbances. On average, the stratosphere also has milder weather and windspeeds compared to the troposphere [9]. Since the aircraft needs to be extremely light, this minimal stress on the aircraft's structure is ideal for long endurance missions. A cruise altitude of 75,000 ft (22.9 km) is just below the altitude record set by the Zephyr of 76,100 ft (23.2 km) [10]. Also, the altitude is high enough that each HALE vehicle has a larger field of view than the aircraft used by the United States Forest Service, and better camera resolution than a satellite in Low Earth Orbit [11]. From an overall system perspective, the HALE vehicle and constellation will function in a similar manner to any other aircraft, needing a base of operations to begin and end missions from. The HALE vehicles will takeoff and constellation coordination will be established. Upon reaching the operational altitude, the vehicles will begin monitoring for wildfires in their search patterns. If a wildfire is detected, the ground station will be alerted. The constellation will continue airborne monitoring until the end of the mission as there is no need to land for refueling due to the solar powered nature of the aircraft. The overall system layout can be visualized in the functional flow block diagram shown in Fig. 2.

[6] Based on a Private Conversation with Dr. Keith Koenig, 2023

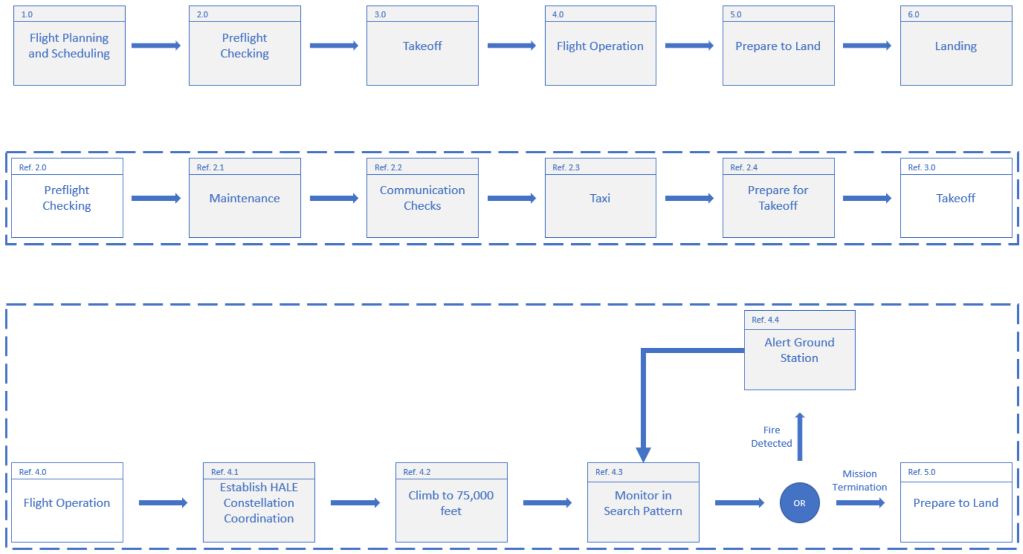

Fig. 2 Functional Flow Block Diagram of HALE Constellation.

The surveillance area selected for this project is the western two-thirds of the state of Colorado. This area was chosen for the frequency of wildfires and the geographic shape of the state. In 2020, Colorado experienced 6,761 wildfires across the state, with most fires occurring in the western portion of the state, making it one of the most fire-ravaged areas in the United States [12]. Additionally, Colorado is geographically rectangular-shaped, making search pattern predictions for initial system testing and analysis a simple process. With the search area selected, the Gunnison–Crested Butte Regional Airport was selected as the ground station where operations will be based and where vehicles will take off from. This airport was selected due to its central location in relation to the search area.

The ideal time frame for operation of the surveillance constellation would fall between mid-March and mid-November. This time frame was chosen primarily due to the detrimental effects high winds have on the flight paths of HALE vehicles in colder months above the state of Colorado. To determine a maximum windspeed threshold, a speed of 70 kts (130 kph) was used to determine whether the aircraft would be able to fly. The 70 kts (130 kph) speed was chosen because it is the estimated cruise speed of the Airbus Zephyr based on its maneuvering speed [6]. Using a two-year sample of windspeeds at operational altitude, provided by analysis of the University of Wyoming Atmospheric Soundings website by Dr. Jamie Dyer seen in Fig. 3, the operational windspeeds are lowest during warmer months over Colorado [13][7][8]. The aircraft constellation would have minimal issue flying during this period since the 70-knot (130 kph) threshold for ideal operation would not be exceeded. Furthermore, since the risk of wildfires is higher during warmer months, the constellation would be able to remain effective despite being non-operational for a portion of the year.

Windspeed
At
h = 75,000ft

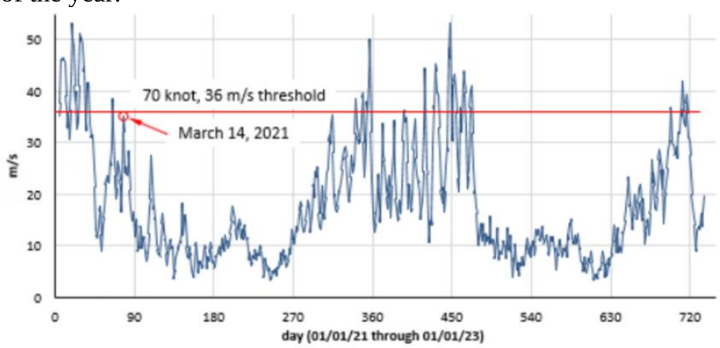

Fig. 3 Maximum windspeed at operational altitude somewhere over Colorado during 2021-2023[7].

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[7] Based on a Private Conversation with Dr. Keith Koenig, 2023
[8] Based on a Private Conversation with Dr. Jamie Dyer, 2023

C. Camera Analysis

To accomplish the mission profile of detecting a wildfire, it was determined that a camera fitted with a CMOS sensor would provide the best information for detecting when a forest fire occurs and the exact location of the fire itself [3]. The Canon 80D was chosen for its inclusion of a CMOS sensor and its focal length (FL) range of 18 mm to 135 mm [14]. Likewise, the Canon 80D has 6000 horizontal pixels (AR) and an array width of 22.5 mm (SS) [14]. The lens magnification equation can be used to determine total ground field of view width, W, and the pixel ground field of view, w[9].

$$\frac{W}{R} = \frac{SS}{FL} \tag{1}$$

$$\frac{w}{R} = \frac{\frac{SS}{AR}}{FL} \tag{2}$$

Equations (1) and (2) are solved for W and w, respectively with the arbitrary constraint that w is less than 10 m to ensure an adequate pixel ground width field of view. Figures 4 and 5 show that as FL increases, W and w decrease. Upon data analysis, it was determined that all values calculated fell below the w constraint, so the FL value that supplied the largest W value of 17.76 mi (27.58 km) was chosen. The 17.76 mi (27.58 km) total ground width was used during the flight path simulations to determine the adequate number of aircraft needed to survey the western two-thirds of Colorado. Furthermore, the results showed how camera characteristics like FL, AR, and SS drive the camera results.

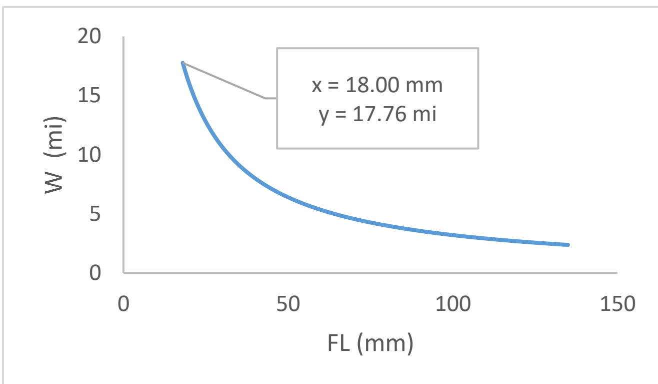

Fig. 4 Total Ground Width Field of View for the Canon 80D at 75,000 ft altitude.

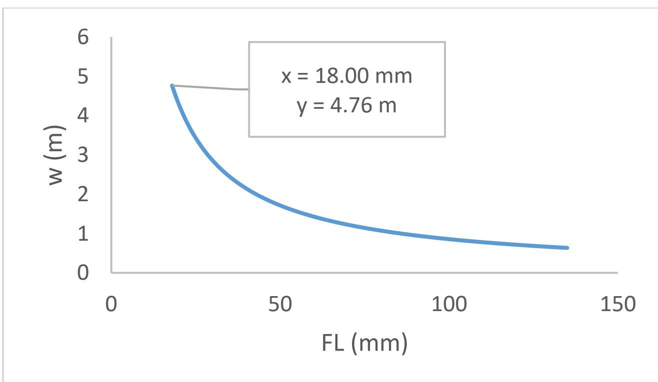

Fig. 5. Pixel Ground Width Field of View for the Canon 80D at 75,000 ft altitude.

[9] Based on a Private Conversation with Dr. Keith Koenig, 2023

D. Flight Path Simulations

Initial research and article reviews revealed that it was necessary to determine the optimal search and survey technique for the HALE system. The two largest factors that influenced the search patterns were the wind speeds at cruise altitude and the field of view for the final camera systems. Research showed the optimal search and survey pattern to locate the fire in the least amount of time and distance traveled to be a grid-based survey technique combined with a sand clock technique as shown in Fig. 6 [15].

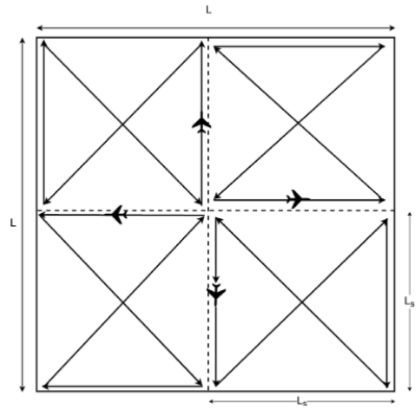

Fig. 6. Optimal Search and Survey Technique from Research [15].

Using the combined approach, the system would fly a grid pattern comprised of smaller sand clock patterns to search for a fire. This technique proved optimal from the research; however, this pattern provided large gaps when scaled to the necessary area for the mission. Despite its efficiency in small area applications, this search pattern would not be sufficient for this application. In addition to the search pattern, the atmospheric winds at the cruise altitude proved to be an important consideration. Through analysis of historical wind data over the state of Colorado, it was discovered that wind velocities were high, especially in the cool season, with a predominant westerly flow (directed from west to east)[10][11]. These high-speed winds would create challenges for the lightweight Zephyr, making westward travel difficult due to the presence of a headwind. Due to these prevailing west-east winds, the team elected to utilize rectangular patterns with a longitudinal long axis to minimize latitudinal travel time and the subsequent influence from high headwinds. A script written in MATLAB was utilized to calculate the number of vehicles needed to achieve complete coverage of the search area along with the flight path coordinates [16]. The approach considered the total ground width visible by the Canon 80D camera at the cruise altitude. The latitudinal and longitudinal distances of the search area were used along with the ground width in order to divide the area into strips of equal widths. The Haversine formula was used to calculate the distance between the Latitude and Longitude coordinates that define Colorado and the search area [17]. These search strips run north and south to mitigate the effects of the large longitudinal winds. With the atmospheric winds incorporated with the 70 kts (130 kph) cruise speed, the HALE vehicle was found to have ground speeds of 76 (141 kph), 44 (81 kph), 102 (188 kph), and 29 kts (54 kph) in the north, south, east, and west directions, respectively. It was determined that seven vehicles would be sufficient to obtain complete coverage of the search area. The search area was not able to be divided into a whole number of equal widths the size of the visible ground width. The number of vertical search lines needed was 13.71 and with each vehicle covering two search lines in the rectangular pattern, 6.85 vehicles were needed to obtain complete coverage of Colorado. As it is only possible to have a whole number of vehicles, the number was rounded up to seven. This created areas of overlapping coverage, but this was preferred over any gaps in the coverage. The total width of coverage overlap in the longitudinal direction with seven vehicles is 5.21 miles (8.38 km). This is the most efficient use of the vehicles, given the chosen camera system. The calculated search pattern coordinates for each vehicle were uploaded to a simulation created in System Tool Kit (STK) using MATLAB [16, 18-20]. The STK scenario was used to simulate the search patterns and compute the access and revisit times for a given point in the targeted area (Latitude: 37.25, Longitude: -108). The simulation and the seven rectangular search patterns over the search area are shown in Fig. 7. Over the course of a day, the aircraft was able to detect the fire three times for 6.92 minutes each time. This allowed the aircraft to have a total coverage time of 20.76 minutes. The maximum time between each pass is 7.84 hours [18].

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[10] Based on a Private Conversation with Dr. Keith Koenig, 2023

[11] Based on a Private Conversation with Dr. Jamie Dyer, 2023

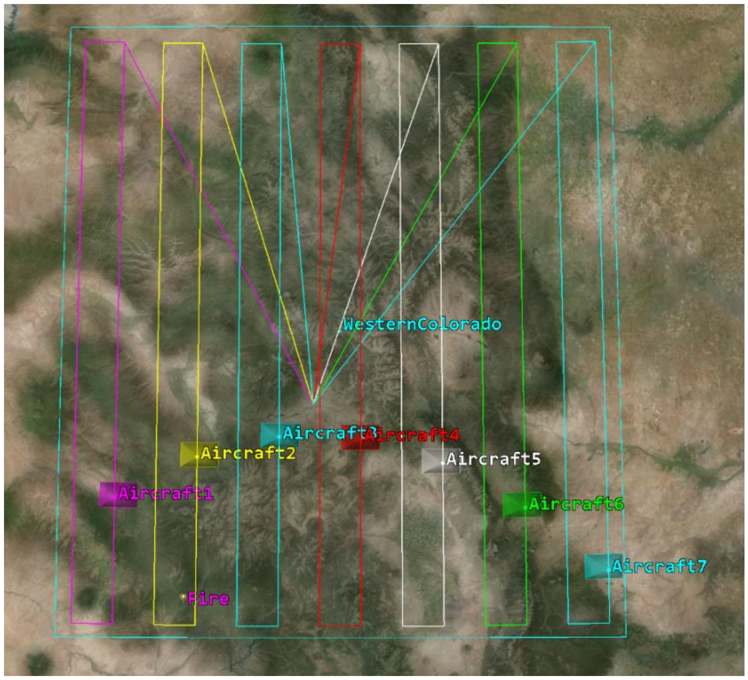

Fig. 7 STK Simulation [18].

E. Testbed Camera Design and Testing Plan

The basis for the proposed fire detection system is illustrated by Fig. 8. Figure 8a shows imagery of a fire from an aircraft-carried hyperspectral sensor. Figure 8b shows the corresponding radiation spectra for two pixels in the image, one in the flaming front and one in a smoke covered area. Both spectra show a spike near 770 nm due to the excitation of potassium in the burning vegetation [3]. This spike can be seen by consumer cameras if their infrared (IR) filters are removed. The proposed system will use a camera with its IR filter and its color mask removed. Narrow-band filters centered at 769 and 780 nm will be used (one at a time), to look for the distinct difference in the spectra at those wavelengths [3].

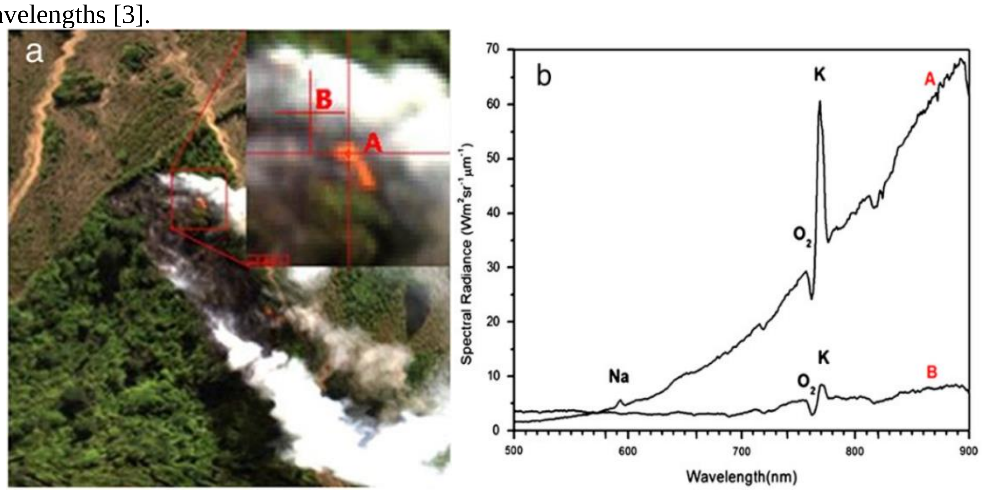

Fig. 8 "HYPER–SIM.GA imagery of Fire 3 (Table 2). (a) True colour composite (R=621 nm, G=569 nm, B=511 nm), highlighting the flaming fire location and the copious smoke production, and (b) the spectral profile of location A (flaming fire; relatively smoke-free) and B (smoke covered fire)." (Quoted from the caption of Fig. 7 in Ref. 3).

The cameras being used for initial testing would be controlled by a Raspberry Pi 4. This initial camera testbed would be smaller and easier to produce than the system that would be used in the final version of the aircraft. The testbed would be the size of a 2U CubeSat (20cm x 10cm x 10 cm). This system uses a single Raspberry Pi 4B computer and a Raspberry Pi HQ camera. A picture of this camera system is shown in Fig. 9. Because this camera system only uses one camera, the two lenses are attached to a rack and pinon gear and servo that changes the lens in front of the camera [21].

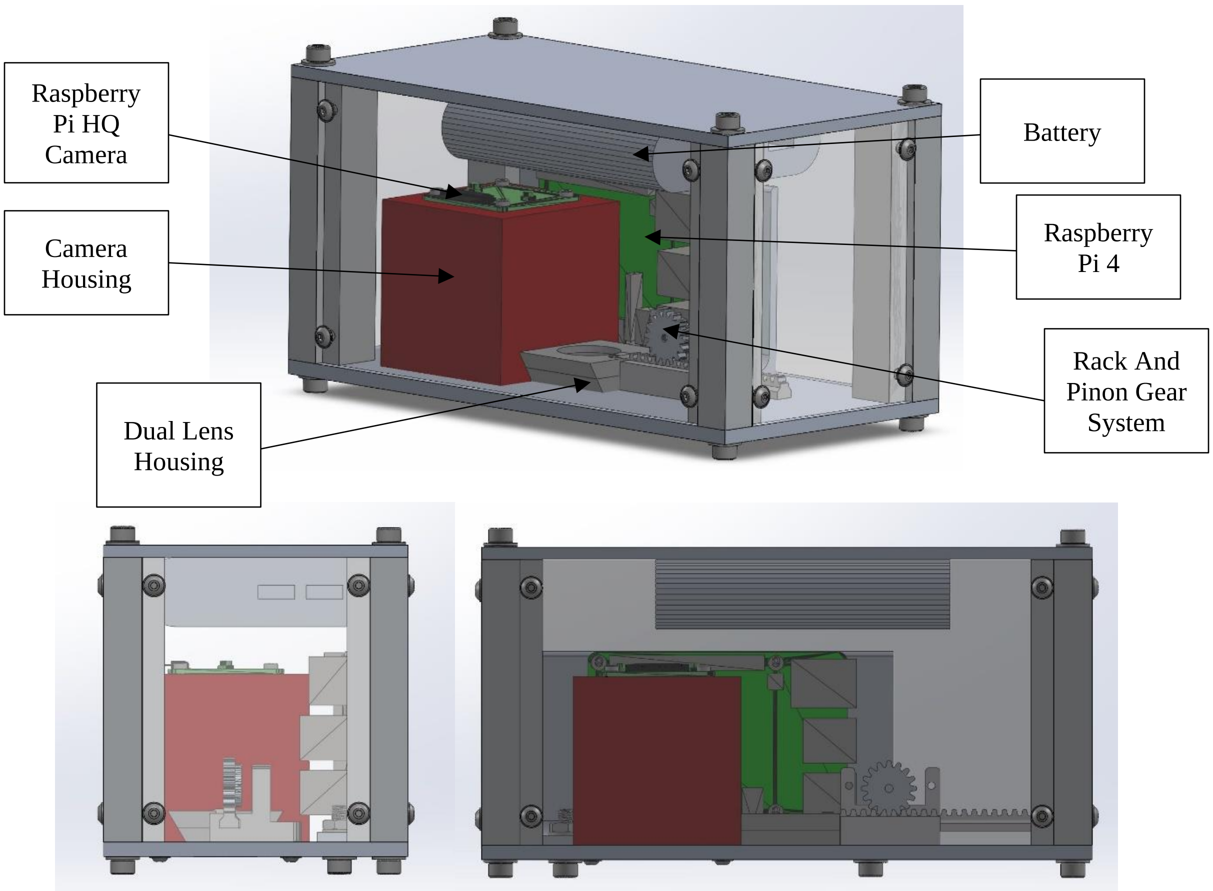

Fig. 9 Isometric View (Top), Side View (Bottom Left), and Front View (Bottom Right) of the Single Camera System [22].

The Raspberry Pi 4 (Ref. [23]) and HQ Camera (Ref. [24]), the servo mount (Ref. [21]), and the rack and pinon gears (Ref. [21]) shown are CAD files pulled from Thingiverse. These parts are cited in the reference section of the paper. The fasteners and L-bracket that support the Raspberry Pi 4 CAD files are from the vendor McMaster-Carr [25]. A table with the McMaster-Carr parts used can be found in the Appendix. The L-Bracket, top plate, bottom plate, and columns are made from 6061 aluminum. The panels from the sides are made from a Static Dissipative and Ultraviolet (UV) resistant acrylic plastic. The camera holder, lens holder, servo holder, and rack and pinon gears will be 3D printed from Polylactic Acid (PLA). The battery would be attached to the top plate using 3M Dual Lock.

Once constructed, the camera systems would be put into the apparatus and attached to a drone from the Raspet Flight Research Laboratory in Starkville, Mississippi. The testbed system would be flown over a series of controlled minor brush fires in a safe and secluded location, and the data would be collected and analyzed. Should the data prove fruitful, the small-scale information and data would be used to apply the system to the team's larger scale theoretical system.

V. Conclusion

A HALE vehicle outfitted with a camera capable of detecting burning foliage would be an extremely useful addition to the wildfire detection systems in areas where wildfires are consistent threats. An aircraft similar to the Airbus Zephyr S would be an ideal choice for long-term surveillance due to its successful long-term flights, light weight, and ability to carry the necessary payload weight for the chosen camera system. The camera itself would have filters capable of detecting only wavelengths emitted by burning potassium in plant matter and would circumvent the issues caused by hot smoke and smoldering ashes. Moving forward, the authors discovered avenues for follow-up work that could prove helpful to the ideas outlined within this document. While researching cameras to integrate into the HALE system, many other CMOS-fitted cameras were found to be on the market. A similar analysis used on the Canon 80D could be completed to see if total ground field of view width, W, and the pixel ground field of view, w vary with different camera systems, provided that camera cost is considered. Furthermore, an overall cost analysis would provide better visibility on how valuable the Zephyr could be compared to other aircraft currently in use to detect wildfires. Additionally, a smaller camera system is being constructed to provide validation of the camera system that will be used in the full-scale version of our wildfire detection system.

Appendix

Table 1. McMaster-Carr Parts List [24].

Part	McMaster P/N
Columns	9146T77
L-Angle Bracket	8982K123
Bottom Plate	89015K259
Top Plate	89015K259
Side Wall Large	8774K23
Side Panel Small	8774K23
Black-Oxide Alloy Steel Flanged Button Head Screws	91355A163
18-8 Stainless Steel Low-Profile Socket Head Screw	92855A845
Metric 18-8 Stainless Steel Thin Hex Nuts	90710A025
Black-Oxide Alloy Steel Socket Head Screw	91251A345
Black-Oxide 18-8 Stainless Steel Washer for Number 10 Screw Size	96765A125
Black-Oxide Class 10.9 Alloy Steel Screws	92137A250
Super-Corrosion-Resistant 316 Stainless Steel Hex Nut	90242A333

Acknowledgments

The authors would like to extend thanks to the individuals that have assisted with this project. Firstly, the authors would like to thank Dr. Keith Koenig (Mississippi State University Aerospace Engineering Dept. Emeritus Professor) for his insights and time dedicated to ensuring the group was well-informed about the capabilities of CMOS sensors in detecting wildfire emissions. Secondly, the authors would like to thank Dr. Jamie Dyer (Mississippi State University Geoscience Dept. Professor) for his time and efforts in providing the authors with an extensive wind data analysis for the area of concern. Lastly, the authors would like to thank Mr. Rob Wolz (Mississippi State University Aerospace Engineering Dept. Instructor) for his teachings and insights through lectures and advisory meetings.

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