ALPHA FOUNDATION FOR THE IMPROVEMENT OF MINE SAFETY AND HEALTH

Grant Number: AFC518-23
"Intrinsically Safe Underground Aerial Reconnaissance Platform Development"

Final Technical Report

United Mine Workers of America Career Centers, Inc.
197 Dunn Station Road
Prosperity, PA 15329

Principal Investigator: Mr. Marlon Whoolery
Phone: 724-322-0169
Email: mttcmarlon@yahoo.com

Period of Performance: August 1, 2017 – September 30, 2018

Table of Contents

List of Figures

List of Tables

2.0 Executive Summary

In response to a major underground mine emergency, mine rescue and recovery personnel require timely, accurate, and reliable information upon which to base their actions. An Underground Aerial Reconnaissance (UAR) system would convey sensors and/or communication equipment into the mine ahead of mine rescue personnel to provide that information. An aerial system approach potentially offers a faster, more agile, longer range, and more economical means of information collection than ground-based reconnaissance options.

A major technical barrier to UAR application is development of an Aerial Vehicle Platform (AVP) capable of effective use in potentially hazardous atmospheres likely to exist during mine rescue operations. To begin the work of overcoming this barrier, a three-task technical approach founded upon a thorough understanding and analysis of actual UAR mission needs was proposed to develop an effective, mission-specific, and potentially safe AVP design. Consultation with government agency personnel, mine rescue team members, and other subject matter experts (SMEs), during the first task, developed a realistic concept of operation (CONOP) based upon a clearly defined mission and an associated list AVP system performance and operational requirements. The second task revealed that no commercially available airframes could address the AVP requirements and identified candidate technology for possible use in custom AVP development. A purpose-designed AVP integrating candidate components was constructed during the third task for flight demonstration and informal intrinsic safety (IS) evaluation, the culmination activity of this proof of concept phase.

Initial flight tests revealed an inherent motor performance issue that prevented the custom-built AVP from consistently stable flight, a necessity for successful testing in simulated mine environments. Since a solution to this unanticipated issue could not be guaranteed within an extended contract period of performance, a roughly comparable commercial airframe was substituted for the AVP airframe. Sensors and object detection/collision avoidance programming were transferred from the AVP to the commercial airframe for flight-testing. While those tests demonstrated generally satisfactory sensor function, they also revealed operational considerations related to the use of UAVs in confined spaces that suggest that a smaller airframe than that developed for the proof of concept AVP would be more effective for the mine rescue application.

An informal discussion of the custom-built AVP design with Mine Safety and Health Administration (MSHA) Approval and Certification Center personnel revealed that the major power elements of the current designed were not capable of meeting current MSHA intrinsic safety requirements. A smaller airframe employing lower power motors and simpler batteries could offer a less challenging path to approval to operate an AVP in potentially hazardous mine atmospheres.

3.0 Concept Formulation and Mission Statement

3.1 Mission Statement

In response to a major underground mine emergency, mine rescue and recovery personnel require timely, accurate, and reliable information upon which to base their actions. A UAR system would convey sensors and/or communication equipment into the mine prior to and/or ahead of entry by rescue personnel to provide detailed measurement of underground atmospheric and ground conditions, assess the condition of mine ventilation controls, advance or re-establish damaged underground wireless communication or monitoring systems, and possibly locate trapped miners. An aerial system approach potentially offers a faster, more agile, longer range, and more economical means of information collection than ground-based reconnaissance options that may encounter impassible or dangerous post-event mine conditions. At this time, a UAR system capable of supporting mine rescue operations does not exist.

Four major subsystems envisioned for a capable UAR system are: (1) an Aerial Vehicle Platform, (2) Underground Navigation, (3) Data Communications, and (4) Sensor Payload(s). A major technical barrier to UAR application is certification of the AVP and its payloads for use in potentially hazardous atmospheres likely to exist during mine rescue operations.

The intent of this proof of concept effort was to develop a thorough understanding and analysis of actual UAR mission needs, then develop and demonstrate an effective, mission-specific, and potentially intrinsically safe AVP design to begin the work of overcoming this barrier.

3.2 Concept Formulation

A three-task technical approach founded upon a thorough understanding and analysis of actual UAR mission needs was proposed to develop and demonstrate an effective, mission-specific, and potentially intrinsically safe AVP design. The first task consisted of a high-level system engineering evaluation. Through consultation with MSHA Mine Emergency Operations (MEO) and National Institute of Occupational Safety and Health (NIOSH) personnel, mine operators, mine rescue teams, and other SMEs, a realistic CONOP based upon a clearly defined mission and an associated list of threshold and objective AVP system performance and operational requirements were developed. Key requirements included desired vehicle mission duration, payload capacity, maneuverability, and operational range. These requirements bound on AVP design considerations including aerial vehicle type, propulsion means, and on-board energy storage needs. Within these design bounds, the second task was focused on identification of candidates for AVP application considering currently available propulsion, power, and on-board control equipment that is either IS or nearly so. During the third task, representative candidate AVP equipment were down-selected for platform integration for an actual flight demonstration and initial IS evaluation, the culmination activity of this proof of concept phase.

Note that while discussion of the Underground Navigation, Data Communications, and Sensor Payload subsystems was included in the meetings with the SMEs, in-depth investigation of these subsystems was outside the scope of this proposal that focuses only on developing an AVP capable of safely maneuvering through hazardous underground atmospheres. Should a future development phase be funded, components for the remaining subsystems would be identified and integrated with the AVP to develop and evaluate a working prototype of a complete, effective UAR system.

3.2.1 Background

Subsequent to an underground mine emergency such as a major fire or explosion, mine rescue and recovery personnel need the best possible information about current mine conditions to guide and focus their response. If mine personnel remain underground following the emergency, response time is especially critical, and actual life-or-death decisions may guide the actions of the mine rescue team. Important information about post-event underground conditions may be obtained by observing the response of in-mine atmospheric monitors and personnel tracking information, if those systems remain in operation. Interviews can also be conducted with personnel that were underground at the time of the event and were able to successfully exit the mine. Mine atmospheric samples may be collected at portals, shafts, slopes, boreholes, or other access points for subsequent analysis. Depending upon the nature of the emergency, however, underground monitoring systems may not remain intact. Since conditions underground may be very dynamic, some personnel interview information may be outdated after only a short time. Due to the time required to collect and analyze mine atmosphere samples from a limited number of discrete points (that may be a significant distance from the actual location of the emergency event), periodic atmospheric sampling can yield only a delayed and inferred indication of current conditions within the mine.

Mine rescue teams monitor the mine atmosphere and collect this and other information as they advance through the mine. However, MSHA is reluctant to have rescue teams enter unknown or poorly understood conditions to avoid placing the team members at risk and possibly compounding an already dire situation. Therefore, NIOSH and MSHA have been jointly developing robotic means of advance mine reconnaissance to eliminate the need to send individuals into uncertain circumstances. These robotic means must be capable of safe operation within the potentially explosive atmospheres that may be encountered underground following a mine evacuation event.

MSHA's ANDROS Wolverine Robot (also known as V2) is a tracked vehicle approximately 50 inches tall and weighing over 1,200 pounds. V2 is equipped with navigation and surveillance cameras, lighting, mine atmospheric detectors, night vision capability, two-way voice communication, and a manipulator arm, and is operated remotely via a 3,000-foot fiber optic cable. Unfortunately, the size and weight of V2 limits its exploration to more open underground areas. Both of the tracked vehicles developed for NIOSH, the Gemini Scout Mine Rescue (GSMR) vehicle and the smaller, more flexible "Snake Robot", have been demonstrated under simulated mine emergency conditions. The GSMR vehicle is designed to be deployed ahead of the mine rescue team and the Snake Robot is designed to be deployed via a borehole. The GSMR vehicle can be operated remotely using radio frequency communication. Both platforms employ cable tethers. For all of these ground-based robots, their trailing cables restrict and constrain their rate of advance, maneuverability, and ability to surmount obstacles encountered in their path, if obstacles on the mine floor can be surmounted at all.

Airborne reconnaissance vehicles capable of maneuvering through the mine could address these range, advance rate, and obstacle passage limitations. Small flying platforms would convey sensors and communication equipment into the mine prior to and/or ahead of entry by rescue personnel to provide detailed measurement of underground atmospheric and ground conditions, assess the condition of mine ventilation controls, advance or re-establish damaged underground communication systems, and possibly locate trapped miners. An aerial system approach potentially offers a faster, longer range, more agile, targeted, and economical means of underground information collection than ground-based reconnaissance options.

However, in-mine conditions during rescue operations dictate that an aerial system must be capable of safe operation in hazardous atmospheres either through explosion-proof (XP) design, IS design or a combination of XP and IS designs. Given that XP rated components are generally heavy and bulky in construction, it is most likely that the components of an effective aerial reconnaissance system entering a mine would have to be designed to meet IS standards.

3.2.2 Task 1: Concept of Operation (CONOP) Formulation

3.2.2.1 CONOP Background

In order to develop a CONOP for UAV use in a mine emergency, a fourfold approach was implemented. First, information was obtained from reviewing experiences in Command Centers during actual mine emergency events. Second, information was obtained by talking to other SMEs with various and differing backgrounds in mine emergency response and mine rescue. Third, an online survey was conducted. The survey was sent to approximately 104 mine rescue experts and personnel located throughout the United States. Fourth, a number of MSHA’s Investigation Reports on major mine disasters were evaluated. This four-fold method allowed the development of a realistic CONOP based on past events, current methodologies, and real-life experience.

Members of the grant investigation team have been involved in over 90 mine emergencies. These include acting as the senior technical advisor and expert in emergency response. They have had a great deal of experience in an active Command Center and working with rescue and recovery operations during mine emergencies. These include:

- the explosion at the JWR No. 5 Mine in 2001 where there were 13 fatalities
- the inundation and rescue efforts at the Quecreek Mine in 2002 where all nine miners were rescued safely

- the explosion at the Sago Mine in 2006 where one miner was rescued and there were 12 fatalities
- the collapse at the Crandall Canyon Mine in 2007 where there were 6 miner fatalities and 2 mine rescuer fatalities
- the Upper Big Branch Mine explosion in 2010 where there were 29 fatalities

This direct, first-hand experience was used in the development of the CONOP.

Information was also obtained by meeting with 38 SMEs in mine rescue and emergency response. Of these 38 experts, 2 were from academia, 13 were from mine operators, 1 was a consultant, 11 were from MSHA, 2 were from NIOSH, 1 was unknown, 7 were from state agencies, and 1 was an equipment vendor. Appendix A presents an affiliation list of these SMEs.

An online survey of mine rescue experts and persons involved in mine rescue was conducted to expand the scope of SME engagement. The survey questions are contained in Appendix B. The results of the survey are presented in Appendix C and discussed in detail later in this report.

Three of MSHA's Investigative Reports of recent major mine disasters were evaluated. This included the JWR No. 5 Mine Disaster in 2001, the Sago Mine Disaster in 2006, and the Upper Big Branch Mine Disaster in 2010. Copies of these reports are available on the MSHA Website (MSHA.gov). A UAV was not available for use in response to any of these disasters. An evaluation was conducted to determine how a UAV could have been employed to aid mine rescue efforts.

The results of the SME engagements and report evaluations indicate that an unmanned aerial vehicle would be a useful tool following a mine disaster. Potential uses include acting as a scout for advancing mine rescue teams, conducting mine exploration and mine atmosphere sampling when it is too dangerous to deploy mine rescue teams, and insertion through a shaft or borehole to obtain information in the areas of the mine immediately adjacent to the shaft or borehole.

3.2.2.2 CONOP Response to Mine Emergencies

In a mine emergency, the personnel in the Command Center are responsible for all of the activities surrounding the event. This includes considerations to safely locate and rescue missing miners as well as initiate mine recovery. The safety of the personnel already underground as well as mine rescue team members re-entering the mine is paramount. It is critical the Command Center has access to as much current information as possible as the response to the emergency evolves. During the initial stages of an event, the information the Command Center has available to make decisions is often limited to that obtained from the mine communication system, escaping miners, and any available gas monitoring data, and a "best-guess assessment" of conditions of the post-event mine infrastructure.

The communications and tracking systems can provide information about the last known location of all the miners at the time of the event. Information from escaping miners allows the Command Center to narrow the location of the area of the mine affected by the event and possibly provide some communications with any missing or trapped miners. In a fire situation, communication with miners that can report on changing conditions can be invaluable in determining the best course of action. However, the communications system may or may not remain in full operation after the event, especially in the affected area, but it should be monitored continuously during rescue and recovery efforts.

Escaping miners can provide information about what they heard and saw during and after an event. Their perspective represents a snapshot of conditions in the mine at a specific point and time. However, conditions can change rapidly especially in a mine fire situation. Additionally, escaping miners may not have been close to the affected area. The information provided by escaping miners can be used by the Command Center to help determine if the rescue team should start exploration from the mine opening or if the team can proceed underground in an expeditious manner to a location closer to the affected area.

Gas monitoring data is critical in determining what options are available to the Command Center. The Command Center personnel must determine if explosive methane-air mixtures exist in the mine and if there are possible ignition sources in the affected area prior to allowing miners or mine rescue teams to remain in the mine or to re-enter the mine. However, the data available to make this determination is generally extremely limited. Initially, it may only be from a few handheld gas readings for methane, oxygen, and carbon monoxide gas obtained from the ventilation return openings at the surface of the mine. Continuous monitoring of these returns can help the Command Center determine the general conditions in the mine and, more importantly, in the affected area. Increasing methane and carbon monoxide gas levels may cause the Command Center to limit underground rescue and recovery operations while steady or dropping gas levels may allow the Command Center to begin underground operations.

However, it is difficult to determine gas concentrations in the affected area based only on gas readings in the surface return locations. The atmosphere at the surface returns are often diluted by splits of air from other areas of the mine. Ventilation may be disrupted in the affected area allowing only a small portion of that air to actually make it to the surface return. Some mines may have an atmospheric monitoring system underground that may help obtain gas information closer to the affected area. In general, these systems are only located in the intake haulage entries to monitor for carbon monoxide gas and may not provide information as to the conditions downstream from the affected area. Additionally, these intake haulage monitoring systems may only be able to detect carbon monoxide gas concentrations less than 1,000 ppm. Eventually, vertical boreholes may be drilled in appropriate locations to better evaluate the gas conditions in the affected area, but these boreholes may take hours to days to be completed depending on the overburden depth and surface conditions. Cameras may be used to evaluate the conditions near the bottom of the borehole. However, these cameras can only provide information immediately adjacent to the borehole. Sampling tubing installed in the borehole will allow the Command Center to better determine the gas concentrations in the accessed area.

Sensors mounted on an unmanned aerial vehicle would allow the Command Center to obtain both visual and atmospheric data in areas of the mine yet unexplored by the rescue team. This would significantly increase the safety of the miners and the mine rescue teams.

3.2.2.3 CONOP Subject Matter Expert Meetings

A series of meetings were held with SMEs to determine their thoughts concerning the use of UAV's in mine rescue. A list of general and specific operational questions was developed to gather information from the SMEs in an organized manner. The list of questions that were used is presented in Appendix D. The following paragraphs summarize the feedback provided by the SMEs during the meetings.

The experts agreed that a UAV could be a useful tool to rescuers in post-event operations. They presented various situations where the additional information obtained by the UAV would help mine rescuers.

The experts indicated that the UAV could benefit and assist the rescuers. They did not believe that a workable UAV would slow them down. They also felt it was important that the UAV be easy to use and have a positive record of accomplishment. Although robotic units have been used in mine rescue previously, their success has been limited. The lack of consistency and an unimpressive performance record limited the confidence in these robotic units. The SMEs agreed that a UAV could follow the same path to skepticism if a positive record of application was not developed and maintained.

The experts felt there were several possible missions for a UAV. They felt the UAV could be used in place of a rescue team when underground conditions were too dangerous to deploy the team. This would include situations when explosive concentration of gasses or nearly explosive concentration of gasses were likely to be present or when a fire was raging out of control. In these situations, the UAV could be used to enter the mine through drift opening, slopes, or shafts to gather additional information and to look for missing miners. The SMEs also agreed that the UAV could be used as a scout for exploring mine workings to assist mine rescue teams. The UAV could explore a few hundred to a thousand feet in front of the team. The experts felt a smaller UAV could be useful if it could be lowered into the mine through a borehole into unexplored areas of the mine to travel a few hundred feet in areas adjacent to the borehole.

The experts felt a group that was able to train with the UAV regularly should operate the UAV. This group could operate it from the surface or from safe underground locations. The UAV's primary function would be to assist the Command Center and mine rescue teams to gather information about the unexplored areas of the mine.

The experts agreed that the primary mission of the UAV should be to gather information to assist the rescuers. The UAV would either travel in front of mine rescue teams (perhaps from the fresh air base) or travel to a mine area where it is unsafe for mine rescue teams to enter. Visual information provided using onboard UAV cameras is critical. The UAV should also have the ability to test for various gases including, oxygen, methane, and carbon monoxide. Infrared thermal cameras would be useful in certain situations to locate hot spots or conceivably missing miners. The ability to communicate audibly could be useful in rescue situations.

The experts agree that the visual information the UAV could gather would help the rescuers by providing a preliminary view of mine roof and rib conditions, possible explosion debris fields, water levels, the state of ventilation control devices, and other mine information. A gas detector is needed either to maintain the safety of teams traveling underground or to better determine if it is safe to allow teams to travel underground. Thermal cameras would be useful in smoke for navigation and to help locate missing miners. The experts agreed that a live video feed would be desirable to obtain the timeliest information. However, if the UAV had the ability to travel using mine coordinates, the still images and stored gas readings from the UAV would still be useful.

The experts varied on who should have the information from the UAV. Generally, they agreed that the Command Center and the exploring mine rescue team should both get the unfiltered information. They also agree generally that exceptionally graphic information should be shared only as needed. The decision to share information with other persons such as the media or family members should be made by the Command Center.

The experts agreed that whoever owned, operated, and maintained the UAV had to be able to use it on a regular basis. A mine rescue team that operated the UAV for an hour or two every month or two months would not likely have the skill level needed to be successful. It is important to maintain the UAV in top working order. It may be appropriate that the MSHA MEO be the primary owners and operators of the UAV. Another possibility would for the UAV to be owned by a private mine rescue company if that company were adequately funded and their only mission were to practice for and then to respond to mine emergencies.

The experts all agree that a UAV should be intrinsically safe or permissible. The risks of a UAV igniting explosive gases is not taken lightly by the mine rescue community. However, there was significant discussion as to the UAV meeting international intrinsically safe standards and for MSHA to also accept these standards.

The experts felt that a UAV that is not intrinsically safe or permissible would have limited missions. Although safety features, such a gas detector that would turn the UAV off, might be helpful, the use of a UAV in a gassy mine would be problematic due to liability concerns if there were missing miners or mine rescue teams present underground.

The experts felt that the Command Center should make the decision as to when and how the UAV should be deployed. They felt that the operators of the system as well as a person with expert knowledge of the mine layout (a "navigator") should direct the UAV's pilot. Mine rescue team members should also be involved.

The experts felt an entity such as MSHA or a private mine rescue company should operate the UAV. They agree that the UAV operator should train with mine rescue teams and expose as many mine rescue teams as possible to this technology.

The experts felt that if payload becomes an issue, the UAV should use a modular concept so that it could be outfitted with the appropriate equipment needed for a particular mission. Sensors and cameras could be changed to suit the needs of the mission.

The experts felt that batteries for the UAV should be able to be changed out underground in fresh air. The batteries should last for the length of the mission. They felt at 20 to 30-minute flight duration period should be needed for mine rescue team use. The mission could also be completed as a one-way trip only if needed (provided a safe UAV power-down capability is available). A longer battery life would be desirable for longer duration missions.

The experts were open to consider novel power systems for the UAV. They agreed the power system should not be overly complex or create additional hazards.

The experts felt that a basic controller should be used for the UAV Operation. A simple and easy system such as a gaming controller was considered optimal.

The experts were open to ideas as far as the propulsion system. A propeller type system seemed reasonable but a lighter-than-air system could be acceptable as long as it could be controlled in the mine environment.

The experts felt the size of the UAV would be dependent on the mission. For example, a borehole deployable UAV should be small enough to fit though an 8-inch diameter cased borehole. A UAV that is deployed in the underground mine should be small enough to fit though a standard 30-inch man door.

The experts were open to ideas as far as UAV guidance and what technology would be available. The UAV should have some type of proximity warning system to prevent collisions with the mine roof, ribs or floor. It would be useful if it could return automatically to its starting location when its mission is complete. It would be useful if it could use mine coordinates to travel through the mine. The experts agreed that operation in a GPS-denied environment and available technology could limit what is available and useful.

The experts had a variable opinion as to the ideal flight range. A mine rescue team typically advance in 1,000-foot increments, so some felt 1,000 feet would be a useful range. Other indicated that a shorter range of a few hundred feet would be useful. A long-term goal would be to have the UAV be able to fly all the way from the mine openings to the furthest working section, a distance which could easily be a few miles.

The experts agreed the UAV should be easy to maneuver in a mine opening and would like the UAV to be able to make turns around 90 degree turns into and through crosscuts but realize that operator-to-UAV radio communications technology would be a limiting factor.

The experts agreed there should be a battery power indicator to allow the operator time to have sufficient power to return the UAV to its base before the lack of power renders the UAV inoperable.

3.2.2.4 CONOP Online Survey

In an effort to acquire a broader perspective of the potential use and utility of UAVs for post-event mine exploration, an on-line survey was built and distributed to the mine rescue team community using the online system offered by Survey Monkey. A survey was built using nine questions and one comment/feedback box. The survey form is included in this report as Appendix B. The questions contained in the survey were designed to generally follow the questions asked during the discussions with the SMEs.

The survey was sent via email to 102 mine rescue team experts across the country on November 15, 2017. In addition, the survey was also distributed through social media to SMEs inside the US Mine Rescue Association, National Mine Rescue Association, Holmes Safety Association and nine collegiate student mine rescue teams. When the survey closed on December 8, 2017, thirty-two responses had been received. A review of survey results reinforces the information that was collected during the face-to-face SME interviews. The summary results of the individual survey question responses are included as Appendix C.

The following are observations from the survey responses:

- 75% of the survey respondents agreed or strongly agreed that an UAV could be a useful tool to rescuers in post-event operations.
- Most respondents believed that the UAV could best benefit or assist rescuers by locating miners and for mine atmosphere sampling.
- 25% of the respondents would not launch a non-permissible UAV if mine rescue teams could not be deployed because of dangerous post-event conditions. Interestingly, 62.5% of the respondents neither agreed nor disagreed to launch a non-permissible UAV.
- One-half of the respondents agreed that the Command Center should make the decision to launch a UAV.
- A clear majority of the respondents believe that the optimal mission flight time should be dependent on the mission and tasks. Those who did respond to a specific flight duration selected between 16 to 45 minutes.
- When it comes to optimal flight range for a UAV for underground use, there were mainly two responses: 500 to 750 feet and >1,000 feet. The response >1,000 feet was clearly the most popular response.
- For the optimal size for an UAV, the most popular responses were evenly divided between 19 to 24 inches and 25 to 30 inches. Note that these size ranges, though popular, may preclude flight through open man doors.
- 75% of the respondents believed that the decision to fly the UAV back to the takeoff point or land in the mine for later recovery should be made by the pilot and that decision depends on available power and the specifics of the mission.
- 25% of the respondents agree that the UAV should have other underground uses in addition to mine rescue team assist. Interestingly, most of the respondents neither agreed nor disagreed that the UAV should have other uses.

3.2.2.5 CONOP MSHA Investigative Reports

Three MSHA Investigative Reports of recent major mine accidents were evaluated. These reports were written after the latest three major mine accidents that affected the mining industry dramatically: the Jim Walter Resources (JWR) No. 5 Mine Disaster in 2001, the Sago Mine Disaster in 2006, and the Upper Big Branch Mine Disaster in 2010. It is important to note that UAVs were not available at the time of any of these disasters. In each instance, an evaluation was made to determine if and how a UAV might have been used to aid mine rescue efforts.

JWR No. 5 Mine Disaster [1]

On September 13, 2001, two separate explosions occurred in the Jim Walter Resources, Inc. No. 5 Mine. These explosions occurred in the 4 Section of the mine at approximately 5:20 pm and

[1] Mine Safety and Health Administration, Report of Investigation, Fatal Underground Coal Mine Explosions, No. 5 Mine, September 23, 2001

6:16 pm resulting in fatal injuries to thirteen miners. Thirty-two miners were underground at the time of the explosions. An initial rescue effort by miners began after the first explosion. The second explosion ended the initial rescue effort by the miners. A Command Center was established that was comprised of officials from Jim Walter Resources, the United Mine Workers of America, the State of Alabama's Office of Safety and Inspection, and the Mine Safety and Health Administration. Two mine rescue teams were assembled. The Command Center determined it was safe for the teams to enter the mine.

The first mine rescue team proceeded underground at around 8:05 pm or about 1 hour 41 minutes after the second explosion. The first team proceeded into the mine and reached the portion of the mine affected by the forces of the explosions. It was approximately 10:05 pm or about 3 hours 49 minutes after the 2nd explosion. As the team traveled in 4 East, they encountered an injured miner and began treating him. Other members of the team traveled further inby to the intersection of 4 Section where two fatally injured miners were located. Two of the team members transported the injured miners out of the mine while the remaining members of the first team explored the area toward Shaft 5-9. The injured miner arrived at the mine surface at 11:30 pm or about 5 hours 14 minutes after the 2nd explosion. The remaining members of the first team located another fatally injured miner and traveled outby away from 4 Section to a working phone and reported the information to the Command Center at 12:05 am or about 5 hour 49 minutes after the 2nd explosion.

Based on the information received from the first team, the Command Center decided the best chance of survival was in the 6 Section. They directed the mine rescue team to explore 6 Section.

The mine rescue team traveled back to 6 Section. They encountered smoke near the roof in the track entry. The ventilation controls in the area were damaged. As they continued into 6 Section, they encountered a fire. As the water lines outby were damaged, they could only use fire extinguishers to battle the fire. The fire extinguishers were not successful. A decision was made to try to extinguish the fire and continue searching for the missing miners. As the team proceeded further in 6 Section, they found the air was no longer moving. They decided to proceed outby to the phone to report their findings to the Command Center.

A second mine rescue team had been sent into the mine and was advancing communications when they encountered the first mine rescue team and together they decided to contact the Command Center. It was now approximately 2:00 am or about 7 hours 44 minutes after the 2nd explosion. The Command Center had the first and second mine rescue teams advance communications and make repairs to the water line as they moved toward 6 Section. The teams did not have enough supplies to reach the fire. They retreated and reported this update to the Command Center. A third mine rescue team was sent into the mine to replace the first mine rescue team. The third mine rescue team reached the fresh air base (FAB) around 5:27 am or about 11 hours 11 minutes after the second explosion. They instructed the first mine rescue team to exit the mine.

The second mine rescue team began to explore near the mouth of 4 Section and into 6 Section. They encountered heavy smoke, 3.1% methane, and 162-ppm carbon monoxide exiting the No. 1 entry of 4 Section. They retreated and notified the Command Center. At 6:25 am or about 12 hours 9 minutes after the 2nd explosion, the Command Center decided to have all teams evacuate the mine. After all teams reached the surface of the mine and were debriefed by the Command Center, it was concluded that the still missing miners could not have survived the effects of the second explosion and the conditions prevented the safe re-entry to recover the victims.

A plan was put in place to extinguish the fire by pumping water into the mine to flood the area. Water was pumped into the mine commencing on September 25, 2001. After the area was flooded, the water was pumped back out of the mine. Mine rescue teams eventually re-entered the mine and on November 7, 2001, the remaining nine victims were recovered and brought out of the mine.

An analysis of the rescue event record reveals that a UAV may have been useful in the following instances to assist in the rescue and recovery efforts at the mine:

- A UAV lowered into the 5-9 Shaft could have examined the area near the 5-9 Shaft and traveled into both the 4 Section and 6 Section. It had the potential to locate the missing miners, the fire burning in 6 Section, and the location of high levels of methane and carbon monoxide. Any of this information would have been useful to the Command Center as they directed teams into the mine.
- A UAV traveling in front of the mine rescue teams as they traveled into the mine could have assessed the conditions in front of them. In addition to visual information, they could have collected information about the mine atmosphere in front of them allowing them to react quickly, if necessary, without being directly exposed. It could have sped up their travel time.
- When the team reported the conditions at the 4 Section and 6 Section intersection, the Command Center directed them to travel into 6 Section. If a UAV was available, they could have sent it into 4 Section while the team explored 6 Section. The UAV may have found the missing miners in 4 Section and may have provided important information about the conditions in 4 Section. If the UAV was sent into 6 Section in front of the team, it may have located the fire and given information about the mine atmosphere prior to the team being exposed to it.
- During the final recovery efforts and the flooding of the mine, a UAV could have been used to evaluate conditions in the mine both during the flooding and during the de-watering process. It could have been used to evaluate the status of the fire and the mine atmosphere prior to sending mine rescue teams into the mine.

A UAV could have been useful during the rescue and recovery efforts at the mine. The additional information it could have provided the Command Center would have helped their decision-making and increased the safety to mine rescue team members and any potential missing miners.

Sago Mine Disaster [2]

On January 2, 2006, an explosion occurred at Wolf Run Mining Company's Sago Mine. Twenty-nine miners were underground at 6:26 am when the explosion occurred. Twelve miners lost their lives. One miner was seriously injured. Mine management personnel attempted an initial rescue effort. They located the 1st Left crew who were walking out of the mine and transported them to the surface. The 2nd Left Parallel crew remained unaccounted for. Mine management personnel were unable to restore ventilation and clear the mine atmosphere and exited the mine at 10:35 am or about 4 hours 9 minutes after the explosion. A Command Center was established comprised of officials from Wolf Run Mining Company, West Virginia Office of Miners' Health, Safety, and Training, and the MSHA. Mine rescue teams were assembled.

Elevated levels of carbon monoxide gas detected at the return air drift delayed the deployment of mine rescue teams to begin exploration. Eventually the carbon monoxide gas levels decreased and the Command Center determined it was safe for mine rescue teams to enter the mine.

The first mine rescue teams proceeded underground at about 5:25 pm or about 10 hours 59 minutes after the explosion. The teams encountered an area where water could eventually affect the airflow, and the Command Center had them restore power to that area and re-start the pumps. Further exploration into the mine commenced again at 8:05 pm or about 13 hours and 35 minutes after the explosion. The team continued exploration until they encountered an energized red light glowing in the belt entry. The risk of having an energized component in the mine caused the Command Center to order the withdrawal of the mine rescue teams from the mine at 2:40 am or about 20 hours and 14 minutes after the explosion. The Command Center did not allow the teams to re-enter the mine until a borehole that was being drilled into the 2nd Left Parallel Section was completed. No response at the borehole was heard from the trapped miners.

Mine rescue teams re-entered the mine to continue exploration at 6:57 am or about 24 hours and 31 minutes after the explosion. They reached the 1st Left crew's abandoned mantrip at 2:13 pm or about 31 hours and 37 minutes after the explosion. They continued exploration and found that all of the seals in the Mains had been destroyed. They began exploration of the 2nd Left Parallel.

At approximately 7:48 pm or about 37 hours and 22 minutes after the explosion, the teams found the 2nd Left Parallel crew's abandoned mantrip. Shortly afterwards they also found evidence of

---

[2] Mine Safety and Health Administration, Report of Investigation, Fatal Underground Coal Mine Explosion, Sago Mine, January 2, 2006

12 opened SCSR's and footprints in an outby direction. They continued the exploration into 2nd Left Parallel. The Command Center directed the team to stretch their communications to reach the faces and sometime before 11:46 pm or about 41 hours and 20 minutes after the explosion, the mine rescue team reached the barricade where the 2nd Left Parallel miners were located. Only one miner was alive and subsequently transported to the surface. By 9:22 am pm or about 50 hours and 56 minutes after the explosion, the victims were recovered and transported to the surface.

The miners from the 2nd Left Parallel had survived the effects of the explosion and attempted to escape from the mine. They apparently decided that they could not escape and decided to construct a barricade and wait for help. Evidence indicated they survived a number of hours after the explosion.

An analysis of the rescue event reveals that a UAV may have been useful in the rescue and recovery efforts including the following.

- Mine rescue teams did not enter the mine for almost 11 hours after the explosion occurred. The Command Center determined it might not have been safe due the concentration of gases exiting the mine. During this period, a UAV could have traveled into the mine and gathered critical visual and atmospheric information. It may have been able to reach the barricade where the missing miners were located.
- The UAV may also have provided enough information for the mine rescue teams to travel to the mouth of the 2nd Left Parallel to begin exploration rather than start at the entrance to the mine. It took the mine rescue teams over 32 hours to reach the mouth of the 2nd Left Parallel. The information provided by a UAV could have resulted in a much different outcome for the missing miners.
- A UAV could have been lowered into the mine through the borehole into the 2nd Left Section. The UAV could have traveled the short distance and located the barricade where the miners were located. That information could have helped the Command Center make critical decisions to get to the missing miners in a more expeditious manner.
- A UAV traveling in front of the mine rescue teams could have increased the speed that they explored the mine. It could have improved their safety by locating the energized light prior to the teams locating it. A UAV could have explored into 1st Left to evaluate conditions and free the mine rescue teams to continue their exploration toward the 2nd Left Parallel. A UAV could also have explored toward the seals in the Mains and allowed the mine rescue team to continue their exploration in the 2nd Left Parallel.
- A UAV could have been used to explore into the 2nd Left Parallel when the mine rescue team reached the mouth of the section. It could have located the barricade and important visual and atmospheric information obtained. The Command Center could have evaluated this information to make critical decisions to reach the missing miners.

- A UAV could have been useful during the rescue and recovery efforts at the mine. The additional information it could have provided the Command Center would have helped their decision-making and even the changed the eventual outcome of this disaster.

Upper Big Branch Mine Disaster [3]

On April 5, 2010, an explosion occurred in the Performance Coal Company's Upper Big Branch Mine-South at approximately 3:02 pm that resulted in fatal injuries to 29 miners. After the explosion, numerous persons (mainly management personnel) entered the mine to determine what had happened and begin rescue operations. They encountered one miner walking with an SCSR, and a mantrip with one injured miner and seven victims. They brought the miners to the surface. Two other company officials continued into the mine. A Command Center was established comprised of officials from Performance Coal Company and Massey Energy, the State of West Virginia's Offices of Miners Health, Safety, and Training, and the Mine Safety and Health Administration. Mine rescue teams arrived and the Command Center began the rescue operations. From April 5 through April 9, 2010, over 20 mine rescue teams worked to explore the mine to locate the missing miners.

The Command Center had a mine rescue team enter the mine by about 6:00 pm or about 2 hours and 58 minutes after the explosion. The team eventually reached crosscut 78 where they encountered damage from the explosion and established a FAB. During the following hours, other mine rescue teams entered the mine and explored much of the area of the mine inby the location of the FAB at crosscut 78. At 12:45 am or about 9 hours and 37 minutes after the explosion, the Command Center directed all personnel to exit the mine after the mine rescue teams encountered explosive gases, elevated levels of carbon monoxide, and smoke. By 2:30 am or about 11 hours 22 minutes after the explosion, the mine rescue teams and other company personnel had exited the mine. There were two injured miners, twenty-five fatally injured miners, and four miners still unaccounted for.

On April 6 and 7, boreholes were drilled into the mine to monitor and attempt to ventilate explosive gases. The return air exiting the mine was monitored to evaluate the atmosphere in the mine. On April 8, the Command Center determined the atmosphere was safe for mine rescue teams to re-enter the mine. At 4:55 am or 61 hours and 47 minutes after the explosion, four mine rescue teams entered the mine and began exploration. They advanced communications and explored parts of the mine. The Command Center ordered them to withdraw from the mine when explosive gas mixtures were detected at one of the boreholes at 9:29 am or about 66 hours and 21 minutes after the explosion.

[3] Mine Safety and Health Administration, Report of Investigation, Fatal Underground Mine Explosion, Upper Big Branch Mine-South, April 5, 2010.

On April 9, the Command Center determined the atmosphere was safe for mine rescue teams to re-enter the mine. At 12:13 am or about 81 hours and 5 minutes after the explosion, four mine rescue teams entered the mine and began exploration. They explored parts of the mine, determined the TG 22 refuge alternative had not been deployed, and explored into the HG 22 Section. The Command Center directed the teams to evacuate the mine when elevated carbon monoxide levels and smoke were encountered in the HG 22 Section. They exited the mine at 9:02 am or about 89 hours and 54 minutes after the explosion. Inert gas was pumped into the HG 22 Section through a borehole to reduce oxygen levels.

On April 9, the Command Center determined inert gas had made the atmosphere safe for mine rescue teams to re-enter the mine. At 4:18 pm or about 97 hours and 10 minutes after the explosion, four mine rescue teams entered the mine and began exploration. Three of the four missing miners were found in HG 22. Teams continued searching for the remaining missing miner. At 11:20 pm or 104 hours and 12 minutes after the explosion, teams located the last missing miner and rescue efforts ceased.

The 29 fatally injured miners were found in five different areas of the mine. The TG 22 crew were on their way out of the mine on a mantrip, the longwall crew was on the longwall face, the HG 22 crew were boarding their mantrip to exit the mine, miners were working on the headgate side of the longwall, and an examiner was near the longwall mother drive.

After the rescue efforts and recovery of the victims was completed, the mine was evacuated and monitored until June 7 when it was determined safe for mine rescue teams to complete a systematic exploration of the mine. During this exploration, the mine rescue teams found one hot spot that had to be cooled with water and at least eight other areas where hot spots had existed but had cooled while the mine was evacuated. These hotspots further justify the need for additional visual and atmospheric information during rescue and recovery efforts after an explosion.

An analysis of the rescue event reveals that a UAV may have been useful in the rescue and recovery efforts including the following.

- The large area affected by the forces of the explosion made it difficult to explore all of the affected area quickly. The mine rescue teams could have used a UAV to more quickly reach each of the refuge alternatives to see if they had been deployed and locate the missing miners.
- UAV could have increased the advance rate of the mine rescue teams, especially with the delays encountered during HG 22 exploration.
- A UAV deployed through boreholes could have gathered visual and atmospheric data in the areas near those boreholes.

- If equipped with an infrared camera, a UAV could have detected the hot spots remaining in the mine before exposing mine rescue teams to those conditions.

3.2.2.6 CONOP

A review of all the information revealed there are three general CONOPs for a UAV. The first and most basic concept would include using the UAV as a scout for advancing mine rescue teams. This is the first step in using a UAV in a mine as it can use existing mine infrastructure and is the least complicated approach. The CONOP for this project was developed using this concept.

The second concept would include using a UAV to conduct mine exploration when it is too dangerous to deploy mine rescue teams. This becomes more difficult because it involves the UAV traveling much longer distances, perhaps several miles, and therefore, there is the need to establish communications for the UAV as it advances into the mine. Long distance mine exploration may require multiple UAVs possessing exceptional flight endurance, use of communications repeater systems, or a combination of both.

The third concept would include using a UAV through a shaft or borehole to obtain information in the areas of the mine immediately adjacent to the shaft or borehole. This concept has challenges as it limits the size of the UAV. Most mine rescue boreholes that are drilled are less than 9 inches in diameter. A deployment method must be developed to get the UAV to the bottom of the borehole. A system would need to be established to allow the UAV to maintain communications while making multiple 90 degree turns to improve its exploration capabilities.

Because of their greater complexity and very demanding technical requirements, developing a CONOP and associated design requirements both for the second and third concepts is not addressed as part of this report.

Mine Rescue Team CONOP

A specialized UAV team would operate the UAV. This team may be staffed by personnel from the MSHA MEO Division (to make this capability available nationwide) or a separate mine rescue consultant (which also might provide nationwide-wide response). The specialized team must have the resources to maintain and practice regularly with the unit. They must also work closely with all mine rescue teams so they can also become familiar with the operation of the UAV in a mine rescue or emergency situation.

The specialized team should have multiple UAV Senior Operators (SO) who would generally be located on the surface of the mine. They could also be located with the back-up team at the FAB. The SO would have communications directly to the Command Center and with the FAB underground. A fiber optic system could be used to connect the surface Command Center to the FAB. This may also be accomplished using the MSHA Communications System. A laptop computer would be set-up and used by the SO and by the back-up team at the FAB. A monitor will also be located in the Command Center. A person from the mine operator who is familiar with the underground workings would assist the SO and serve as a navigator

The UAV should have the following capabilities and characteristics:

- The UAV should be less than 30" wide and battery operated.
- The UAV must be intrinsically safe, at least as required by international standards.
- The UAV should be equipped with the minimum of a low-lux camera and an associated light source. An infrared camera, still camera, and microphone are optional.
- The UAV should have a gas detector and should read the range of gases encountered in percent for oxygen and methane and in ppm for carbon monoxide. It should be capable of providing a warning when pre-set gas levels are encountered. These readings should be displayed on both laptop computers and on the monitor in the Command Center. The gas detector could be either integrated into the UAV or deployed as a separate payload to be deposited by the UAV at an advance location.
- The UAV should be radio controlled using a frequency optimal for underground operations and one that will not interfere with the normal mine rescue radio system or MSHA's Communications System.
- The UAV must be equipped with a shroud or other propeller guards to protect the propulsion system from obstacles. A radar-based proximity detection system to prevent the UAV from running into objects is desirable.
- The UAV should have a "return to home base" function if it begins to travel out of radio range. This autonomous function should follow the normal openings in the mine and not try to return in a direct straight line.
- The UAV should also have an emergency shutdown system controlled by the SO.
- The UAV controller should be easy to operate and based on existing gaming system controllers.
- The UAV should have a minimum operational flight time of 20 minutes.
- There should be a battery life indicator on the laptop computers. The laptop computers would record flight events, power consumption, gas readings and video images from each mission.
- UAV batteries must be replaceable underground and extra batteries must be available to be changed at the FAB after every mission.

As the advancing mine rescue team and the back-up team are setting-up the FAB, the UAV communications station should be established and manned by the back-up team. A back-up team member would allow the UAV to launch from a location above the mine floor to prevent the UAV from entraining rock dust from the mine floor into the atmosphere. The SO would operate the UAV and travel distances up to 1,000 feet in the entry where the FAB is located. Once the UAV has reached the specified distance, it would return to the FAB and the advancing mine rescue team can begin to explore. At the FAB, the battery could be changed out and the UAV inspected and prepared to redeploy by the back-up team. After the advancing team has traveled the specified distance, the FAB would be advanced and the cycle would repeat.

3.2.3 Task 2: Candidate Technology Investigations

Task 2 had the goal of identifying, within the bounds of the mission CONOPs and functional requirements elicited from the SME's during Task 1, both existing candidates for potential AVP application and individual components for propulsion, power, and on-board control equipment that were certified as either IS or could possibly be modified to achieve certification.

3.2.3.1 Requirements Summary

Based upon Task 1 engagement with mine rescue SMEs, the investigative team's collective mine rescue and underground technology development experience, and an understanding of current UAV technology capabilities and limitations, operational requirements for the AVP were identified.

The proof of concept objective was to develop and demonstrate an effective, mission specific, intrinsically safe AVP design for use in potentially hazardous atmospheres likely to exist during mine rescue operations. A primary assumption for this design was that the AVP would be operated/controlled from a location with a non-hazardous atmosphere so that the only requirement the AVP has to meet IS standards.

Tables 1 through 3 categorize realistic and achievable minimum (threshold) operational requirements for the proof of concept demonstration AVP along with objective requirements for a future prototype.

Table 1: AVP Requirements (1 of 3)

Platform System	Requirement		Value		Requirement Source	Related Requirements
	Number	Description	Threshold	Objective		
General						
	G-1	Capable of safe operation in hazardous atmospheres	Zone 1	Zone 0	4/28/17 proposal language	AF-3, AF-4, PS-2, PS-8, GN-5, GN-6, GN-9, CD-1
	G-2	Able to manuever through and successfully negotiate most underground coal mine obstacles	X		4/28/17 proposal inference	AF-1, AF-2
	G-3	Provide useful information to mine rescue teams		X	4/28/17 proposal inference	CD-2, CD-3, P-3
	G-4	Offer a faster, more agile, longer range, and more economical means of information collection than ground-based reconnaissance options		X	4/28/17 proposal language	G-6, AF-1. GN-7, GN-8
	G-5	Intrisically safe design certified by MSHA for use in continuous explosive atmospheres		X	SME response inference	PS-2
	G-6	Effective operational range	>500'	>1000'	SME response inference	PS-1
	G-7	Mission duration (flight endurance)	>20 min.	>30 min.	SME response inference	PS-1
Air Frame						
	AF-1	Highly maneuverable in all 3 dimensions with sufficient power to operate in some airflow	X		SME response inference	G-2, G-4
	AF-2	Maximum dimension	≤ 30 in.	< 30 in.	SME response inference	G-2
	AF-3	Rugged construction with emergency landing/collision/crash-tolerant physical configuration	X		SME response inference	G-1
	AF-3a	Protective enclosures for rotors	X		Second slide of 12/14/17 presentation	
	AF-4	Inherent flight stability (in case of single or multiple motor failure)	X			G-1
	AF-5	Adequate payload (lift) capacity to accommodate mission sensors	>500g	>1000g	4/28/17 proposal language	P-1
	AF-6	Enable rapid sensor attachment/replacement/exchange		X		

Table 2: AVP Requirements (2 of 3)

Platform System	Requirement Number	Requirement Description	Value Threshold	Value Objective	Requirement Source	Related Requirements
Power Supply						
	PS-1	Adequate to support necessary mission duration (flight endurance)	>20 min.	>30 min.	SME response inference	G-6, G-7
	PS-2	Capable of achieving IS certification	Zone 1	Zone 0		G-1, G-5
	PS-3	Ability to replace exhausted power supply underground rapidly and safely		X	SME response inference	
	PS-4	Current status (remaining life) indicator	X		SME response inference	
	PS-5	Suitable to power flight control electronics	X			
	PS-6	Suitable to power communications equipment	X			CD-1
	PS-7	Suitable to power potential payload sensors		X		P-3
	PS-8	Safe remote power-down for in-mine landing inby (for later AVP recovery)	X		Second slide of 12/14/17 presentation	G-1
Guidance/Navigation						
	GN-1	Platform can/will be flown by a highly trained operator.	manual flight control	semi-autonomous control	SME response inference	
	GN-2	Flight guidance/navigation does not have to be highly automated	X		SME response inference	
	GN-3	First person video (FPV) image feed for operator control	X			CD-2
	GN-4	Auto hover with release of controls	X			
	GN-5	Auto return to immediately prior location upon loss of communication signal		X		G-1
	GN-6	Automatically land with the push of a button	X			G-1
	GN-7	Return to last established waypoint		X		G-4
	GN-8	Return to origin via series of sequential, established waypoints		X		G-4
	GN-9	Operator must be able to easily set and override any programmed flight control functions		X		G-1
	GN-9a	Maintain programmed distance from floor and/or roof	X			
	GN-9b	Quick-reacting, programmable range, collision avoidance system (vertical and horizontal)		X	SME response inference; Second slide of 12/14/17 presentation	

Table 3: AVP Requirements (3 of 3)

Platform System	Requirement		Value		Requirement Source	Related Requirements
	Number	Description	Threshold	Objective		
Communication/Data						
	CD-1	Platform control and sensor data transmission scheme should enable robust non-line-of-sight (NLOS) operation.	LOS operation	NLOS operation	SME response inference	G-1, G-3, P-3d
	CD-2	Ability to stream video images (visible and/or IR)	X			G-3, P-3a, P-3b
	CD-3	Direct integration with common mine and/or special rescue communication systems desirable		X	SME response inference	G-1, G-3, P-3d
	CD-3a	Integrate with MSHA MEO communication system		X	SME suggestion	
	CD-3b	Integrate with IWT underground communication technologies		X	SME suggestion	
Payload(s)						
	P-1	Additional mass	>500g	>1000g		AF-5
	P-2	Intrinsically safe	Zone 1	Zone 0		G-1, G-5
	P-3	Types				G-3
	P-3a	Low lux color video with self illumination	X		Second slide of 12/14/17 presentation	G-3, GN-3, CD-2
	P-3b	Infrared video with real-time selectable color palettes	X		SME response inference	G-3, GN-3, CD-2
	P-3c	Atmospheric sampling		X	SME response inference	G-3
	P-3d	Communication node or repeater unit		X		G-3, CD-1,CD-2, CD-3

3.2.3.2 General IS Requirements

A fire or explosion will occur when an ignition source is present in an atmosphere containing the proper ratio of combustible material and oxygen. Combustible materials may be flammable gases, organic dusts, ignitable fibers, or ignitable metals. In an underground coal mine, the two primary combustible materials are methane gas and suspended coal dust. Therefore, any electrical equipment operating in the presence of such materials must be designed and engineered so that it cannot become an ignition source.

Locations with possible risks due to explosive atmospheres are called “hazardous” or “classified” areas. In North America (the United States and Canada), these areas are historically classified with the “Class/Division/Group” system. In Europe, and the rest of the world, but now more commonly in North America, the “Zone” system is used. Both systems evolved over the past 100 years from efforts by several industrial safety organizations. These organizations needed to categorize both the risk level and required protection techniques and methods for each area to develop standards for electric and electronic equipment construction and protection to permit safe operation.

In the Class/Division/Group system, Class defines the general nature of the hazardous material in the surrounding atmosphere, Division defines the probability of hazardous material being present in the surrounding atmosphere, and Group defines the type of the hazardous material present. Tables 4 and 5 indicate the distinctions for both Class (using Roman numerals) and Division (using Arabic numerals). Group designations employ capital letters with Groups A, B, C, and D characterizing different gas compositions (Class I only) and Groups E, F, and G characterizing dusts and other airborne solids (only for Class II or III).

Table 4: Hazardous Area "Class" Categories

Class	Nature of Hazardous Material
Class I	Hazardous because flammable **gases or vapors** are present (or may be present) in quantities sufficient to produce explosive or ignitable mixtures.
Class II	Hazardous because combustible or conductive **dusts** are present (or may be present) in quantities sufficient to produce explosive or ignitable mixtures.
Class III	Hazardous because ignitable **fibers** or airborne solids are present (or may be present) in quantities sufficient to produce explosive or ignitable mixtures.

Table 5: Hazardous Area "Division" Categories

Division	Probability of Hazardous Material
Division 1	The substance referred to by class has a **high probability** of producing an explosive or ignitable mixture due to it being present continuously, intermittently, or periodically or from the equipment itself under normal operating conditions.
Division 2	The substance referred to by class has a **low probability** of producing an explosive or ignitable mixture and is present only during abnormal conditions for a short period of time - such as a container failure or system breakdown

Alternatively, the "Zone" system follows a method of area classification as developed by the International Electrotechnical Commission (IEC) based upon the probability of hazardous material being present in an ignitable concentration in the surrounding atmosphere. As indicated in Table 6, the Zone system identifies three levels of hazard for gas or dust where the Division system has two. Table 6 also presents the required relative Equipment Protection Level (EPL) associated with each Zone.

Table 6: Equipment Groupings by Protection Level and Application Condition

Zone Grouping	**Equipment Protection Level (EPL) (provided by techniques in this grouping)**	**Industrial Application Condition (frequency of occurrence of explosive atmosphere)**
Zone 0	Highest	Continuous or nearly continuous explosive atmosphere
Zone 1	Moderate to High	Frequently occurring explosive atmosphere
Zone 2	Low	Infrequent presence of explosive atmosphere
No Requirements Zone (NRZ)	None	Negligible occurrence of an explosive atmosphere

International agreement and understanding have been reached regarding appropriate and effective means to achieve the EPL associated with the operating conditions associated with each zone. Table 7, adapted from a recent technical paper[4], compares the internationally accepted means to those available to and applied by MSHA as currently specified by the Code of Federal Regulations (CFR). Table 7 also introduces the concept of evaluating equipment risk based upon whether or not ignition is possible considering no faults (i.e., normal operation), the application of one physical fault, or the application of two faults combining to produce the highest possible discharge current and voltage levels.

The Calder et.al. paper provides a thorough evaluation of the differences between the international and MSHA standards and their application which was not repeated here. Note that for their safety evaluations, MSHA considers that the equivalent of Zone 0 conditions exist inby the last open cross-cut in an underground coal mine under normal operating conditions. Therefore, only electrical equipment approved by MSHA as either IS to a two-fault failure standard or housed in an MSHA-certified XP enclosure is currently allowed to operate inby. The potential for a

[4] Calder, W., Snyder, D., Burr, J.F., "An evaluation of the Relative Safety of U.S. Mining Explosion-Protected Equipment Approval Requirements Versus Those of International Standards", SME Annual Meeting February 19-22, 2017, Denver, CO; Preprint 17-009

compromised atmosphere associated with major mine emergency environments dictates that MSHA certification is required for mine rescue equipment operating inby an established fresh air base, assuming that personnel still remain in the mine.

Table 7: Allowable Protection Techniques by Zone and Regulatory Recognition

IEC Zone Group	IEC/ISA and US NEC 505 Approved Protection Technique	MSHA Similar Technique (allowed inby and in hazardous mine atmospheres)
Zone 0 Applications	Intrinsic Safety (IS) – 2 fault	IS – 2 fault
	Encapsulation	None (except as part of IS)
Zone 1 Applications	Intrinsic Safety (IS) – 1 fault	None
	Flameproof (FP) enclosure	Explosion-proof (XP) enclosure
	Powder fill	None
	Pressurization	None
	Increased safety	None
	Oil immersion	None
	Encapsulation	None
Zone 2 Applications	Non-sparking	None
	Non-incendive (a.k.a. IS for Zone 2)	None
	Enclosed break	None
	Restricted breathing	None

For the UAR aerial platform application, the mass, bulk, entrance gland designs, and routine maintenance requirements associated with XP enclosures make their application to develop an aerial platform capable of MSHA approval undesirable. Use of an XP enclosure, or enclosures, would be the approach of last resort. Therefore, from an MSHA-approval perspective, the best approach for aerial platform development is make the airframe, its propulsion system, power supply, and sensor payload completely IS to a two-fault standard.

Tables 8 and 9 offer a list of potential AVP intrinsic safety issues or concerns associated with each of the platform subsystems. This list focuses only on the platform as it is assumed that it would be the only part of the UAR system entering a potentially hazardous atmosphere while it is operated/controlled from a location with a non-hazardous atmosphere. Of all the listed subsystems, it may be anticipated that those that may pose the greatest IS challenges are the Power Supply, Propulsion, and Navigation and Guidance.

Unanticipated release of stored energy is a major IS concern, so careful attention must be paid to the means of providing the AVP with the power necessary to execute its mission. The Power Supply subsystem must be adequately protected and its output controlled. Minimizing overall AVP power demand would assist in obtaining any IS approval. One potential advantage of the UAR platform is that many of its elements may have relatively modest power requirements with relatively low voltages and currents. With the proper precautions to limit excessive current flow to both to protect onboard electronics and to prohibit rapid discharge that might lead to component overheating or create sparks in case of catastrophic device damage or failure, replaceable batteries can be employed inby. Numerous small devices using replaceable batteries ranging from flashlights to voice amplifiers to two-way radios have received MSHA IS certification.

Table 8: Potential AVP Intrinsic Safety Issues or Concerns (1 of 2)

Platform System	Possible System Options	Related Concern(s)	Possible Solution Approaches
Power Supply	Lithium Polymer (LiPo) batteries	Normal heat of operation	Dissipate with a heat sink
		Overheating due to excessive load or rapid discharge	Protect with current limiting circuits
		Thermal runaway, battery explosion	High quality fabrication standards and product quality control
			Adequate, reliable charging system control to eliminate overcharging, detect cell internal faults or deterioration
			Protection from and inspection for physical damage
	Other battery chemistries	Normal heat of operation	Address if in excess of 85-deg. C.
		Thermal runaway	Address individual root cause(s)
	All batteries	Rapid electrical discharge	Install current limiting circuits
		Disconnection during operation	Secure with vibration and crash-proof fastener(s)
	Fuel Cells	Normal heat of operation	Address if in excess of 85-deg. C.
		Supply cylinder rupture	Physically harden or protect cylinder
		Other gas distribution system leaks	Minimize number of connections; employ rugged, positive connectors
Power Distribution	Wires/cables	Loose terminal connections	Solder and insulate all connections
			Employ positive locking, insulated connectors
	Circuit boards	Short circuit by external means	Employ insulating coating(s)
		Short circuit by internal means	Provide adequate spacing/separation, protection between leads
	Induction	Short circuit by external means	Protect from physical damage

Table 9: Potential AVP Intrinsic Safety Issues or Concerns (2 of 2)

Platform System	Possible System Options	Related Concern(s)	Possible Solution Approaches
Propulsion	Brushless motors	Excessive individual power draw	Employ multiple smaller motors
		Normal heat of operation	Use heat sinks to maintain temperature below 150 deg. F
		Overheating if motor rotation is prohibited	Guard propellers; introduce current limiting circuits
	Propellers	Static electrical build-up/discharge	Employ wood or other certified non-static materials
			Operate above specified minimum relative humidity level
Navigation/ Guidance		Electronic processing component failure	Introduce diagnostics and automatic system shutdown protocol(s)
	Pressure sensors	Operating power	Component selection
	IR range finders	Operating power	Component selection
	Ultrasonic range finders	Operating power	Component selection
	IR cameras	Internal power storage	Identify and address specific design issues
	Visible light cameras	Internal power storage; external illumination power	Identify and address specific design issues; component selection
	Lidar units	Internal power storage	Identify and address specific design issues
Communication/Data	Operating frequencies	Interference from/with other key systems	Frequency spectrum use and informed selection
		On-board antenna power	TBD
		Antenna exposure	Integrate into airframe
Airframe Crash Resistance/Recovery		Power supply protection	Airframe design
		Power distibution protection	Airframe design
		Spark generation due to impact	Employ non-sparking external construction materials
			Surround UAV with protective cage
Payload Sensors	Gas detectors	Pre-existing IS certifications	Sensor selection

The brushless motors listed under the Propulsion subsystem are almost universally employed by UAVs. However, they operate with electrical currents that are significantly higher than those required by most other AVP subsystem electrical components. Therefore, they would be the platform's primary power consumers and dominate the requirements placed upon the Power Supply subsystem. Their inherent power demands, as presented, may exceed MSHA intrinsic safety guidelines. If this proves to be the case, then an alternative means to achieve an approval for the AVP to operate in a potentially explosive atmosphere must be investigated and developed. Notice in Table 7 that the second of two internationally approved protection techniques for Zone 0 includes "encapsulation". MSHA may also consider this a viable technique under certain circumstances. While the definition of "encapsulation" for IS purposes needs to be defined in the context of the AVP application, there may be options to implement this approach to advantage in a custom platform design.

While some of the issues or concerns dealing specifically with the platform electronics might be addressed through implementation of 2-fault design standards, others may not. In the instance where necessary electronic circuits to implement the desired Navigation and Guidance functions are already designed, developed, and implemented on other commercial platforms, they probably would not conform to the 2-fault design requirement. Complete review and re-design of these circuit boards and sensor components may not be economically feasible, especially as many competing manufacturers develop them, the capabilities of the components employed are constantly improving, and a state-of-the-art design today may well be obsolete in three to four years.

Therefore, the general elements of AVP design philosophy from the perspective of safe underground operation to support mine rescue operations included:

- Compact, streamlined airframe profile with no exposed propellers
- Implementation of suitable collision avoidance technologies
- Rugged, resilient construction to protect batteries and electronics in case of and subsequent to any crash landing
- Use of IS components where applicable and available
- Encapsulation of non-IS components to isolate them from potentially explosive atmospheres.

It was known both that no UAV had previously received MSHA certification for use in hazardous environments and that no initial AVP design could fully attain MSHA standards for certification. Therefore, the project adopted the approach of developing a proof of concept platform (the AVP) to address SME mission requirements and then present that platform for subsequent discussion with MSHA. Provided with tangible AVP design elements (some resulting from current commercial component availability and actual construction issues), MSHA could then more effectively consider and identify specific items of concern to be addressed in a subsequent prototype design.

3.2.3.3 Market Survey

A survey conducted of UAVs (a.k.a. "drones") revealed only four (4) vehicles that claim to be designed and constructed for use in potentially hazardous conditions. Table 10 lists these and summarizes their basic attributes. The following paragraphs elaborate upon each of these drones and their potential suitability for underground application.

Table 10: UAVs Designed for Use in Hazardous Atmospheres

Manufacturer	Model	Type	Intended Use	IS Rating(s)	Physical Dimensions (LxWxH) (inches)	Air Frame Weight (lbs)	Payload Capacity (lbs.)	Payload(s)	Approximate Maximum Flight Duration (minutes)	Power Supply	9/30/18 Status
Larson Electronics	EXDR-LE10-CMR-R1	dual prop quad copter	monitoring and surveying hazardous industrial work facilities	Zone 1 Class I, Div. 1 & 2 Class II, Div. 1 & 2	66 x 60 x 30	21	12.3	infrared and/or visible cameras, data transmitters, gas monitors	22	LiPo batteries	available for purchase
Parrot	Bebop 2 C1D2	quad copter	site inspections	Zone 1 Class I, Div. 2 (assumed)	15 x 15 x 3.5	1.1	TBD	fixed orientation visible light camera	25	LiPo batteries	unknown, not yet released
SAN JORGE Tecnologicas	ATEX DRONE	quad copter	inspection of enclosed vessels	ATEX Zone 0; IECEx Class 1 Div. 1 (anticipated)	12 x 12 x 4	TBD	TBD	fixed orientation visible light camera	unlimited	compressed air	under development
Xamen Technologies	LE4-8X DUAL	dual prop quad copter	chemical plant maintenance or diagnostic operations	ATEX Zone 2	48 x 48 x 12	9.25	2.6	visible light and infrared cameras, gas sensors	8 - 15	LiPo batteries	available for purchase

The Larson Electronics EXDR-LE10-CMR-R1 (Figure 1) is by far the largest and heaviest of the four drones. This should be anticipated since it was designed not only for open-air industrial site inspection and assessment but also for material delivery. It is reported to be certified for service in Class 1 Division 1 (a.k.a. "Zone 1") areas defined as those "where ignitable concentrations of flammable gases, vapors, or liquids are either likely to exist under normal operating conditions or exist frequently because of maintenance/repair work or frequent equipment failure". Several unsuccessful attempts were made to contact Larson (based in Texas) with the intent of determining which agencies issued the drone's certification, if Larson is the actual manufacturer of the drone, and the details of its design that enabled it attain Zone 1 level of certification. Catalog price for the EXDR-LE10-CMR-R1 is $83,000.

The Larson drone is much too large for effective use in most underground environments and has a maximum flight duration only slightly greater than the threshold requirement for the mine rescue UAV. Its cost is also prohibitive.

Figure 1: Larson Electronic EXDR-LE10-CMR-R1 dual quadcopter

The Parrot Bebop 2 C1D2 (Figure 2) apparently was intended to be a hardened version of the popular Bebop 2 model that the French company Parrot has developed and successfully marketed in several variants over the past three years as an economical hobbyist or sport UAV. Parrot is expanding the application of the Bebop 2 design into commercial markets with the introduction in late 2017 of the Bebop 2 Thermal model that carries both visible and infrared cameras. The Thermal UAV is intended for use in building inspection and civil (fire, police) support applications such as search and rescue.

Figure 2: Parrot Bebop 2 C1D2

The C1D2 (presumed to stand for Class 1, Division 2 operation) version for industrial inspection in "hazardous areas" was advertised on a third-party website. The C1D2 appeared attractive as the basis for a potential Task 3 demonstration unit not only because it was designed to achieve some level of safety certification but because of its compact size, proven and tested basic design, and relatively low cost (originally advertised at $3,500). Representatives of Parrot in the United States were contacted in an effort to obtain detailed C1D2 specifications including safety certifications either applied for or obtained and to determine actual product development status and future availability. These inquires revealed that the C1D2 was neither designed nor marketed by Parrot; apparently, an "after-market" developer intended to make modifications to the Parrot product and sell the modified units. The C1D2 was originally advertised for release before the end of 2017. As of October 12, 2018, the website advertising the C1D2 continued to indicate a release date in the last quarter of 2018.

The San Jorge Tecnológicas ATEX DRONE (Figure 3) was another small UAV specifically intended for use in enclosed spaces classified as Zone 0 where a continuous or nearly continuous explosive atmosphere may be present (see Table 6). What makes the ATEX DRONE unique is that it employs motors that are pneumatically powered (instead of electrically powered) thus eliminating a major design concern related to a potential ignition source.

Figure 3: SAN JORGE Tecnológicas ATEX DRONE concept

Conversations with San Jorge in late 2017 revealed that this small Spanish company (less than a dozen individuals) conducts applied research based upon the interests and background of its principal scientists who are also university professors. Their ATEX DRONE concept has been patented in the EU, but is barely out of its first incarnation of physical development. The drone's pneumatic flight motors are powered through an umbilical tether connected to an air compressor maintained in fresh air. The umbilical also serves as a means of communication with the drone through fiber optic cable. The power (lift) of the current pneumatic motor/propeller combination has been tested and measured. Four (4) motors have been installed on a COTS quad-copter platform about 20 inches in width for limited flight control and stability testing. San Jorge's initial concept is to use and support a tether ~30 meters (~100 feet) in length, sufficient for inspection of the interior of oil storage tanks and similar confined spaces. Additional payload capacity is anticipated to be about 100-200 grams, about the mass of a video camera and its LED illuminator.

The primary advantages of the San Jorge UAV design are (1) the elimination of electric motors and (2) availability of an essentially unlimited power supply and, thus, mission duration. The major drawbacks of this design for underground applications are associated with the umbilical tether that would both severely limit the exploration range of the UAV and undoubtedly become tangled or caught on objects within the mine.

San Jorge has also considered the possibility of having a drone carry its own supply of compressed gas to power pneumatic motors and thus eliminate the umbilical tether. San Jorge was asked to perform an analysis of the feasibility of using pneumatic motors supplied by a pressurized tank carried on an untethered platform. San Jorge estimated that for an aerial platform of the size projected for the mine rescue application, a flight duration of only 2-3 minutes might be possible due to the great volume demand of the individual pneumatic motors and the limited capacity of any reasonably sized onboard pressure tank.

Figure 4: Xamen Technologies LE4-8X Dual

Xamen Technologies of France claims that their LE4-8X Dual was “the first ever UAV compliant with explosive atmosphere operations to investigate areas where there is a risk of explosion due to the presence of gas and/or vapor”. This UAV is also a dual quadcopter design slightly smaller than the Larson UAV. The LE4-8X Dual is approved for use in Zone 2 areas as defined in Table

6 as having an "infrequent presence of explosive atmosphere". It is intended for outdoor inspection and assessment of chemical and petroleum processing plants. One notable design feature of this drone is its use of wooden propellers to eliminate the possibility of static build-up and discharge. The MSRP for this drone is approximately $120,000.

Contact with Xamen in November 2017 to discuss IS design features of the LE4-8X Dual and the nature of the intended underground application resulted in the terse reply that "I'm sorry but our drone can't operate inside." This drone is also quite large for effective use in most underground environments, claims a maximum flight duration only 15 minutes, and is likely the most expensive of the four UAVs identified.

Market Survey Summary

In summary, of the four identified "hazardous atmosphere" UAVs, the two commercially available models are both much too large and do not offer the necessary level of safety certification for unrestricted use in an underground coal mine. The smaller Parrot and San Jorge models profess to have acceptable physical dimensions for underground application. Unfortunately, neither is currently offered as a commercial product and neither has a documented IS rating. The pneumatic tether required by the San Jorge model limits both its range and maneuverability. The actual development status of the Parrot UAV remains unknown.

3.2.3.4 Other AVP Design or Technology Possibilities

The two allowable approaches to attain approval for Zone 0 equipment operation presented in Table 5 above are IS to a two-fault standard and encapsulation. These approaches provide general guidance for overall IS AVP design. Other specific requirements include exposed surface temperatures that do not exceed 85 degrees Celsius (185 degrees Fahrenheit) and exposed electrical power discharge incapable of igniting an explosive atmosphere under the two-fault standard. MSHA generally applies a 0.3 milli-Joule minimum ignition energy limit for methane-air atmospheres. There may be other limitations imposed on the use of specific technologies because of potential hazards associated with their use or if they are abused (i.e. specific battery chemistries).

The UAR platform IS concerns listed in Tables 6 and 7 above identify seven different AVP subsystems where IS issues may be encountered and addressed. Within this framework of IS approaches and subsystem concerns, novel technology or design options which may assist future attainment of the program objectives are discussed in the following sections.

Construction Methods

It may be impossible to avoid all obstacles while maneuvering the AVP through the enclosed space of an underground mine, especially under obscured visual conditions. Therefore, physically protecting the drone from collisions should be a high design priority. Many commercial drones designed for outdoor use provide protection for the drone's propellers either as part of the inherent design or as an option. Most commonly, the propellers are protected only from lateral contact in the plane of propeller rotation. However, in the underground environment, contact may occur from any direction. Three examples of fully caged drones are discussed in the following sections.

Flyability Elios

Flyability is a Swiss company founded in 2014 concentrating on building safe drones for operating indoors, in complex and confined spaces, and in contact with people[5] The Flyability Elios is claimed to be the first collision-tolerant drone, designed for the inspection and exploration of inaccessible places. As seen in the figure below, the drone is completely surrounded by a gimbaled, carbon fiber cage about 18 inches in diameter allowing it to fly in complex, cluttered, or indoor spaces. Elios has been used for stope inspection in a Canadian underground palladium mine.

Figure 5: Flyability Elios drone and control unit

[5] https://www.flyability.com/

Skypersonic Skycopter™

Skypersonic™ is a metro Detroit-based research and design engineering company providing autonomous systems and vehicle technology services as well as real-time location systems for various industries[6] *[http://www.skypersonic.com/]*. Skypersonic™ has developed Skycopter™ drones (Figure 6) for indoor applications and for commercial, industrial, agricultural and civil purposes.

Figure 6: Skypersonic Skycopter™

Skycopter™ is a ready-to-fly product suitable for several applications, such as surveillance, indoor inspection, and logistic features, enabled by an embedded high-definition camera. Its copter propeller apparatus is enclosed and protected by a fixed but flexible external cage to ensure safety, and is designed to work indoors, which means that it is very quiet, easy to fly, robust and not sensitive to bumps. It has multiple operative functions, such as flying, rolling, and traveling by land.

Skycopter™ mounts an ultra-bright LED system for applications in complete darkness. Skypersonic also integrates the drone with its Skyloc technology, a real time localization and monitoring system able to control and track with high location accuracy the instantaneous movement of the drone flying indoors or elsewhere where GPS is not available.

[6] http://www.skypersonic.com/

ASU/Honeywell CANARY Tunnel Inspection Drone

The CANARY Tunnel Inspection Drone is a joint development of Honeywell and Arizona State University (ASU) to enable interior inspection of pipes, large conduits, utility passages, and other long enclosed confined spaces[7]. The CANARY features an exterior cage that can roll about a single axle. It is also designed to permit easy inter-changeability of different sensor modules (visible light camera, infrared camera, lidar scanner), as indicated in Figure 7. The CANARY can also drop a communications repeater unit to enable longer-range operation and continued operation around corners.

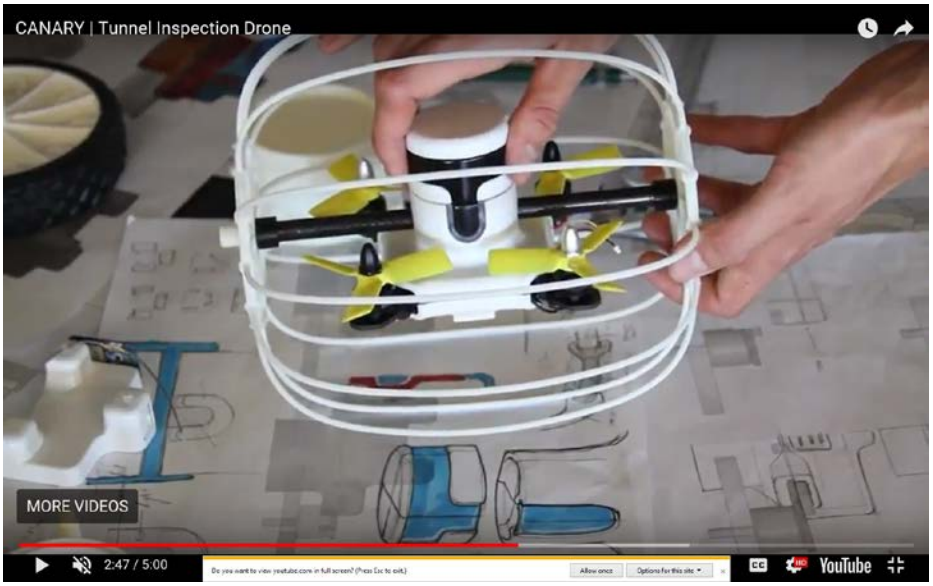


Figure 7: ASU/Honeywell CANARY drone with interchangeable sensor module

Even if protected by an external cage, the AVP may still be subject to crash landings possibly due to foreign object passage through the cage, loss of operator communication, or an on-board subsystem failure. Therefore, the basic AVP structure must also be rugged enough to survive such an event without suffering significant damage. In fact, this may be vital consideration to enable encapsulation to be permitted as a viable IS design approach; a crash landing should not expose any encapsulated non-IS components.

Nanyang Technological University 3D Printed Drone

One means of providing both a crash-tolerant AVP structure and insuring maintenance of component encapsulation might be the approach taken by researchers at Nanyang Technological University, Singapore, who 3D-printed a ready-to-fly drone with embedded electronics using

[7] https://www.youtube.com/watch?v=ETZyCgFjRWs

aerospace-grade material.[8] The electronics were incorporated in the drone during the 3D printing process, which used Stratasys ULTEM™ 9085 high-strength, lightweight FDM material certified for use in commercial aircraft.

Figure 8: Nanyang Technological University 3D printed drone

NTU's Singapore Centre for 3D Printing (SC3DP) and Stratasys Asia Pacific, a subsidiary of Stratasys Ltd., a 3D printing and additive manufacturing solutions company jointly developed the drone. The quadcopter with four rotors was created digitally layer by layer with the drone's electronics embedded in the printed material, a challenge, as most electronic components are not designed to withstand the high temperatures of the 3D printing process. Commercial grade electronics were therefore modified and placed within the drone at the various stages of the printing process. They survived the high temperature printing which reached over 160 degrees Celsius, compared to the usual 80 to 100 degrees. Only the motors and the propellers were mounted after the entire chassis was completed. In addition to being extremely rugged, the 3D printed drone was capable of supporting a mass of over 60 kg (132 pounds) suspended from its structure.

San Jorge Tecnológicas Magnetic Couplings

In any typical drone design, the electrically powered motors wouldl pose a particular IS design challenge. While the brushless motors available for the drone application should not under normal conditions create sparks (as motors with brushes and rotating armatures do), they still may consume multiple watts of power, depending upon the platform's lift and torque requirements. There is always the potential that a damaged or contaminated brushless motor could fail in a manner that would permit an internal short that could create a spark.

[8] http://media.ntu.edu.sg/NewsReleases/Pages/newsdetail.aspx?news=a153e5b5-d315-4d9e-bd5b-6f23108dd0ee

Encapsulation of brushless motors to both protect and isolate them from the ambient atmosphere may also be possible. In addition to developing the ATEX Drone, San Jorge Tecnológicas also designs and fabricates magnetic couplers. Introduction of a magnetic coupler would eliminate the need for actual physical contact between the rotating core of a brushless motor and the shaft of the propeller driven by that motor. The motor would be totally enclosed thus isolating it from any explosive atmosphere while preventing foreign matter from interfering with motor operation, a common mode of failure.

Two potential drawbacks to magnetic coupler use are elevated motor operating temperature and the introduction of additional weight. Motor overheating is a possible brushless motor failure mode that could occur inside a sealed, unventilated enclosure. Thus, identification and use of motors specifically designed to operate at elevated temperatures would be desirable. Also, the magnetic coupling enclosures can be designed to optimize heat dissipation and perform as a heat sink. While adding coupling mass may be unavoidable, this too can be optimized through careful construction material selection and design.

Table 11 presents approximate size and mass calculations of magnetic couplings developed by San Jorge Tecnológicas for three different power motors. The capabilities of the different motors span the likely range of brushless motors that might be used in AVP design. The mass of the couplings does not appear to become prohibitive until approaching the largest motor evaluated which is over two times more powerful than the second motor.

Table 11: San Jorge Tecnológicas Preliminary Magnetic Coupling Analyses

	Motor 1	**Motor 2**	**Motor 3**
Power (Watts)	18	212	472
Nominal Speed (RPM)	7500	7500	7500
Torque (Nm)	0.023	0.27	0.6
	Coupling 1	**Coupling 2**	**Coupling 3**
Diameter (mm)	20	34	45
Length (mm)	10	13	13
Torque (Nm)	0.06	0.6	1.18
Safety Factor	2.5	2.2	2.0
Mass (gm)	25	90	155

These are only first estimations based on a nominal 1-millimeter (mm) thick titanium coupling encapsulation, at least in the gap between the two sets of magnets. If the distance between magnets is increased, the transmitted torque is significantly reduced leading to a heavier coupling solution. Further thermal analysis must be performed after the power consumption of the actual AVP motors is known.

Flight control/guidance/navigation/collision avoidance

In addition to hardening the construction of the AVP, another approach to assist in protection of the platform (as well as making it easier for the operator to use) is to implement specific flight controls and introduce collision avoidance capabilities.

Currently available technologies to assist or enable platform guidance and control include:

- Inertial measurement systems (IMUs)
- Global positioning system (GPS)
- Radio signal ranging
- Image comparison/monitoring
- Barometric pressure sensing
- Infrared (IR) ranging
- Ultrasonic ranging
- Laser ranging/LIDAR scanning

For the underground mine application, the effectiveness of some of these technologies is severely limited or totally impractical due to the absence GPS signals, broad area lighting, or other supporting infrastructure. Therefore, flight control means employed on many commercial UAVs are not viable candidates for use on the AVP.

As one example of a guidance system integrating several sensor technologies is a small UAV, the Phenox2, developed by a Japanese graduate student in late 2015 that can fly autonomously and stably without need for the global positioning system, or a remote controller.[9] The Phenox2 (Figure 9) was a compact quadcopter that weighed only 75 grams and was the first commercially available drone of its size that could fly autonomously and whose flight program could be changed freely by its user.

In a demonstration, the Phenox2 took off, rose to about 1.5 meters above the floor and hovered there without swaying from side to side or up and down. When the operator pushed Phenox2 to one side with a hand, the drone returned to its original position quickly and smoothly and kept hovering since it could confirm and fine-tune its location in real time. To determine altitude, the drone employed an ultrasonic distance meter. A downward-pointing camera imaged the floor to confirm and maintain its location based on the camera images.

[9] https://asia.nikkei.com/Tech-Science/Tech/Tiny-autonomous-UAV-flies-without-GPS

Figure 9: University of Tokyo student Ryo Konomura holds his Phenox2 drone

A more involved approach to provide UAV guidance in GPS-denied spaces involves a monocular camera and a 2D laser rangefinder combined into a hybrid laser-camera sensor to provide information for fusion with data from an on-board inertial measurement unit (IMU). Investigators at the Institute of Systems Optimization (ITE) at the Karlsruhe Institute of Technology (KIT) in Germany have been working on this promising approach that does not use GPS.[10] The camera and laser-range finder were initially calibrated by focusing from multiple different adjacent locations on one object, and so determining the attitude and translation between the two sensors. Basic navigation without GPS is established using the acceleration and angular rate information provided by the IMU, but inertial drift rapidly decreases accuracy, so aiding is essential. The aiding solution has several components which are first integrated together. The camera sensor provides an initial "keyframe" from which relative motion can be derived. Using the initial keyframe, subsequent images provide estimated motion relative to the keyframe providing bounds to combat IMU drift.

Another, and perhaps more useful vision-based approach was announced in October 2017 by researchers at the University of Zurich who introduced the usefulness of a kind of dynamic vision sensor for autonomous UAV guidance called an "event camera".[11] Event cameras differ from regular cameras, but their application appears to be well suited to assisting guidance of small, fast moving vehicles and detecting the presence of objects.

Instead of recording what a scene looks like, as a conventional camera would, event cameras record how a scene changes. An event camera viewing a scene that is not changing does not register any response. However, as soon as the camera moves, it detects that motion on a per-pixel basis and at a very high (millisecond) refresh rate. If the objective is avoiding objects while moving,

[10] http://gpsworld.com/new-developments-in-uav-navigation-and-control

[11] http://www.thedrive.com/aerial/14674/university-of-zurich-researchers-successfully-test-event-based-drone-camera

application of event camera technology might be effective since it just identifies pixel changes, it is sensitive to very low light, and will not be blinded by bright light.

Researchers at the University of Zurich used a prototype sensor called DAVIS that embedded an event camera inside of the pixel array of a standard camera, along with an IMU synchronized with both events and frames. With it, their quadrotor UAV could autonomously fly itself, even under the kinds of lighting changes that would cause a regular camera to fail, such as low-light environments and scenes characterized by a very high lighting contrasts (one side of the room highly illuminated and another side of the room dark).

The event camera technology is currently in a prototype development and testing stage and may not be commercially available at reasonable cost for several years.

Given that the underground mine rescue environment would have no ambient light and may have an atmosphere obscured by smoke and/or dust, the performance of guidance methods that rely strongly upon visual imaging would be adversely affected. However, substitution of imaging produced by longer infrared wavelengths may provide a means to overcome those limitations. Video cameras that detect reflected emissions from infrared LED illuminators can also provide detailed images through partially obscured atmospheres. Infrared cameras that image ambient thermal differences require no illuminators, perform very well in complete darkness, and can detect temperature differences through moderately dense smoke and dust, if sufficiently sensitive.

4.0 Proof of Concept Technology Components

Identification or development of a representative candidate AVP for intrinsic safety evaluation and flight demonstration was the culminating technical activity of this proof of concept phase.

The completion of Task 2 demonstrated that no commercially available drone possessed an overall system IS certification applicable for use in the hazardous areas of an underground coal mine. Also, no commercial-off-the-shelf (COTS) drone possessed important design and/or function attributes that would allow it to fly successfully in a compromised underground mine environment and execute a mine rescue mission. Therefore, during Task 3, system engineering principles and processes were applied to develop and build a custom design based upon the requirements developed during Task 2. The intent was to demonstrate and evaluate the attributes and performance of available technology for a mine rescue mission.

The following sections describe the AVP design process leading to system component selection and assembly.

4.1 AVP Design Process

Use of a subcontractor with extensive UAV development experience was determined to be the most efficient means to deliver an effective demonstration unit while still adhering to the project schedule. The AVP functional requirements listed in Table 3 were reduced to ten (10) specific, quantifiable design criteria. These criteria were presented to several UAV design houses to initiate discussion for design and fabrication of a custom-built AVP.

Four custom drone builders were contacted to determine their capability to engineer, construct, and test a custom proof of concept AVP. Three construction shops responded positively: Charlotte UAV of Charlotte, NC, DroneWorks of Binghamton, NY, and Skypersonic of Detroit, MI. Charlotte UAV subsequently declined further engagement due to a possible intellectual property ownership conflict associated with an indoor drone they were developing for the nuclear industry. Drone-Works and Skypersonic both submitted proposals, and follow-up discussions were held with both to address questions, assure true understanding of the project objectives, and better assess their capabilities to address those objectives

A side-by-side comparison using thirteen vendor selection criteria was prepared to facilitate proposal evaluation and contractor selection. Drone-Works would start with no pre-conceived notions and assemble a drone using COTS components that would enable the vehicle to address the threshold requirements. Skypersonic offered a variant of their existing Skycopter product (see Section 3.2.3.4), possibly making them more efficient in delivery, but more constrained in design. DroneWorks was selected because of their apparent broader knowledge of potential component options and greater flexibility in airframe design and flight guidance approaches. A subcontract was executed on March 13 after a revised final proposal was received from DroneWorks.

Drone-Works' mechanical engineer/designer subsequently created, from the list of ten AVP design criteria, the requirements verification matrix of Table 12 to initiate further discussion, document how individual requirements would be verified, and guide the overall design process.

Therefore, Table 10 presents both (1) the key AVP mission requirements and (2) the elements of the proof of concept AVP evaluation protocol.

Table 12: AVP Mission Requirements and Evaluation Protocol Matrix

Requirement Number	Requirement Title	Shall Statement	Verification Method Summary	Verification Method
AVP-1	Manuverability	The aircraft shall be capable of manuevering in all 3 dimensions when operated by a highly trained pilot.	Flight manuverability will be shown during demonstration flights.	Demostratrion
AVP-2	Maximum Dimension	The airframe shall not exceed 30 inches in any dimension when in flight configuration.	The airframe will be inspected and measured to ensure that no dimension exceeds 30 inches.	Inspection
AVP-3	Useful Payload	The aircraft shall have a payload capacity between 500 and 1000 grams.	The aircraft will be flown with a payload of 1000 grams.	Demostratrion
AVP-4	Operational Range	The aircraft shall be able to maintain positive control link for at least 1000 feet when flown within visual line of sight.	The aircraft will be flown to a distance of 1000 feet.	Demostratrion
AVP-5	Flight Duration	The aircraft shall be capable of maintaing a hover between 20 and 30 minutes.	The aircraft will be hovered in place with a payload of 1000 grams.	Demostratrion
AVP-6	Rotor Enclosure	The aircraft shall have a protective enclosure around the rotors.	The airframe will be inspected to verify that the rotors have a protective enclosure.	Inspection
AVP-7	Crash Resistance	The aircraft shall be of rugged construction with an emergency landing/collision/crash-tolerant physical configuration.	The aircraft shall be subjected to an unpowered drop from a height of 6 feet (TBR) to a concrete floor without (1) suffering any structural damage to its primary airframe and (2) exposing any of its electronic components (including batteries and motors) either to damage or the ambient atmosphere, if originally isolated from that atmosphere.	Demostratrion
AVP-8	Hazardous Area Operation	The aircraft shall be constructed to allow its safe operation in hazardous atmospheres	The aircraft and its material parts list shall be inspected to verify construction either (1) with electronic components that possess an intrinsic safety certification, or (2) in a manner isolating electronic components from contact with any explosive atmosphere, or (3) some combination of (1) and (2).	Inspection
AVP-9	Obstacle Sensing	The aircraft shall be equipped with sensors that allow it to sense obstacles on all six sides (Front, Back, Left, Right, Top, and Bottom).	The design will include the appropriate sensors for flight-test performance evaluation in an enclosed space	Demostratrion
AVP-10	Centering Flight Mode	The aircraft shall have a flight mode where it attempts to center itself within its environment for operation in an enclosed environment.	The aircraft will be flown in an environment demonstrating the centering capability.	Demostratrion

Subsequent basic design considerations focused on the pros and cons of three motor layout options, two hexacopter and one quadcopter. The three layout options as shown in Figure 10 are constrained by the AVP-2 30-inch maximum dimension requirement listed in Table 12.

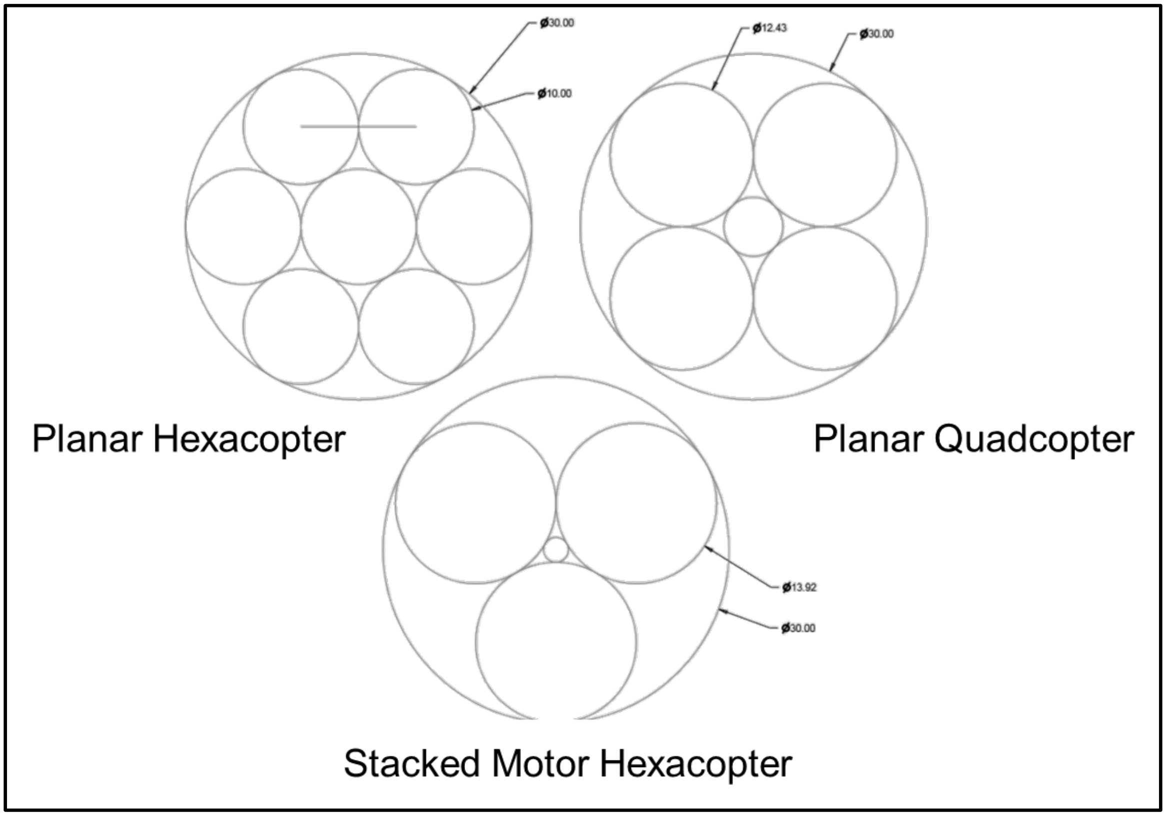


Figure 10: Potential AVP design options

Greater propeller diameter offered greater lift efficiency necessary to address requirement AVP-3. Hexacopter designs (either planar or stacked) provide greater flight stability following the loss of a motor, if sufficient lift for flight can be maintained. However, brushless motors rarely fail in normal service, and institution of a preventative maintenance program with periodic replacement of motors on a regular schedule can mitigate the potential risk of motor failure.

Given the other design challenges involved, the decision was made to pursue the simpler quadcopter design for the proof of concept AVP. A quadcopter involved a lower component count (motors and motor controllers, wiring for power distribution, fewer structural elements) resulting in less weight while still accommodating large diameter propellers offering more lift. In addition, the quadcopter allowed the best compromise between propeller diameter and central area needed for flight control electronics and mission payload.

Based upon the design requirements listed in Table 10 and the fundamental quadcopter layout decision, DroneWorks prepared for review and discussion a Conceptual Design Review (CDR) package that presented different design options. The envisioned AVP was a flat, fully enclosed cage structure similar to that shown in Figure 11 that would better enable flight through thin-seam mines or access to other underground areas with constricted height. This design type also would permit unobstructed camera images (unlike a fully caged structure), facilitate aircraft transportation and handling between flights, and enable direct access to the aircraft batteries for rapid exchange.

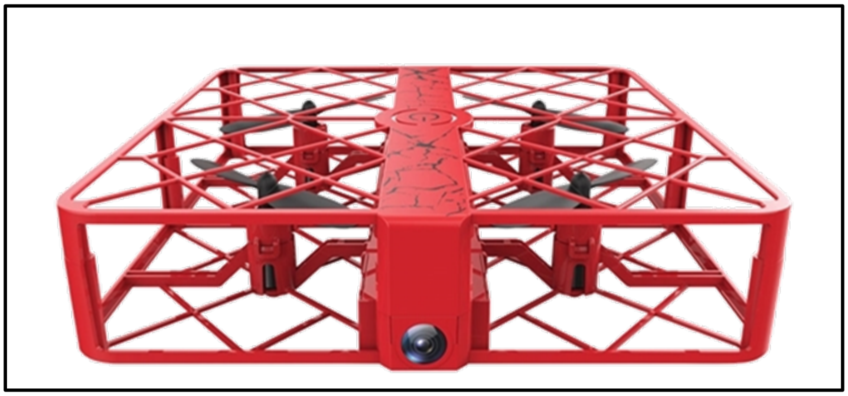


Figure 11: An appealing UAV style with a flat, fully enclosed cage structure

The CDR also offered options for on-board power supplies and brushless motor selection including the method to measure delivered thrust versus power consumption for different motor and propeller combinations. Other discussion topics included the effective measurement range of obstacle detection sensors to be arrayed around the AVP and selection of one of three common communication frequencies for platform flight control.

Following additional information exchange and refinement, selection of specific CDR options in mid-April 2018 initiated the beginning of actual AVP design. An apparatus similar to the one shown in Figure 12 employing load cells to measure thrust was used to test multiple propellers on different motors to determine which motor/propeller combinations would yield optimal performance.

Figure 12: Apparatus to measure motor and propeller combination performance

Figures 13 and 14 represent sample data collected from the apparatus for the motor/propeller combination identified as providing the best overall performance.

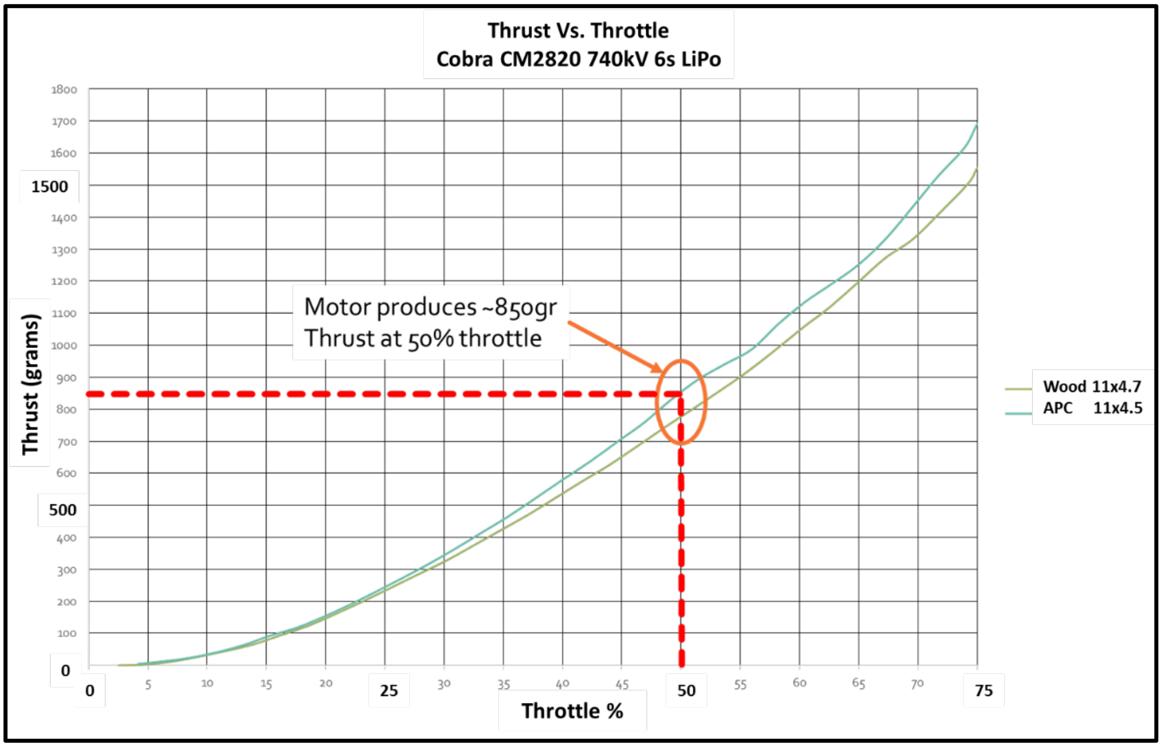


Figure 13: Selected motor thrust vs. throttle with two different propellers

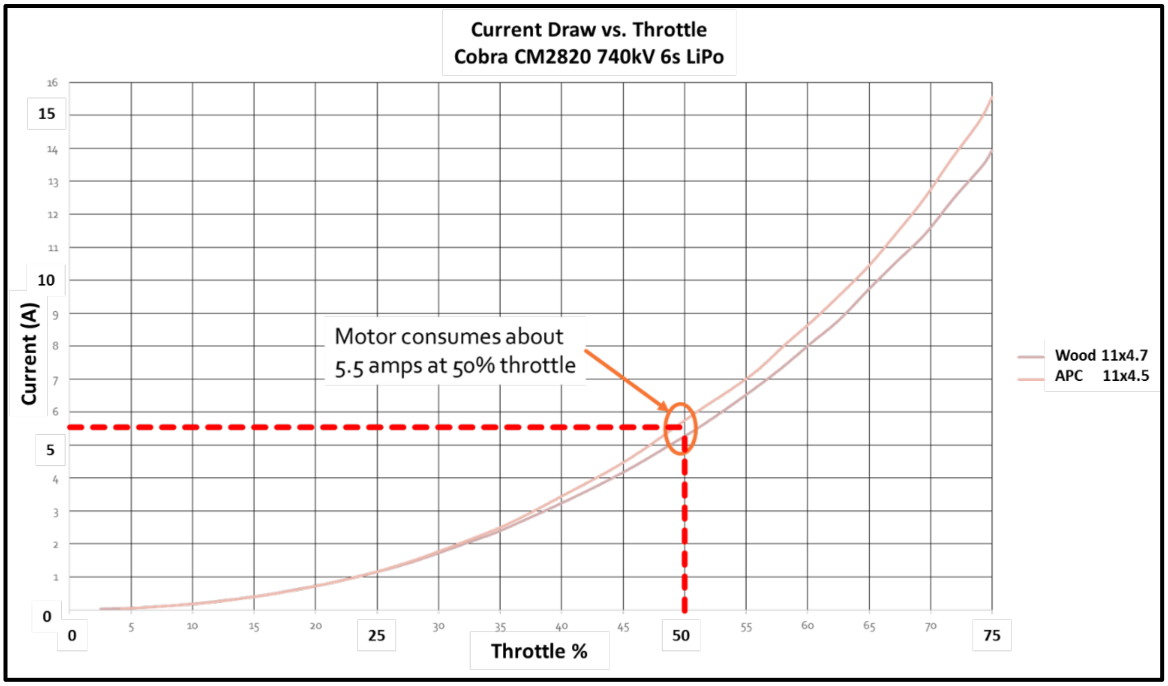


Figure 14: Selected motor current vs. throttle data with two different propellers

To calculate an estimated AVP design flight time, data from Figures 13 and 14 and the following assumptions were employed:

1. The total AVP weight is equal to the total thrust generated by four motors at 50% throttle.
2. A combination of two, 6-cell lithium-polymer (LiPo) batteries would provide their rated capacity.
3. Only 80% of battery capacity is consumed.

As shown in Table 13, an estimated flight time of nearly 25 minutes was calculated for the custom-built AVP design. This flight duration is consistent with design requirement AVP-5 in Table 12.

Table 13: Flight Time Estimate Analyses for the Quadcopter AVP Design

Flight Time Engineering Analysis	
Battery Capacity	11.400 Amp-hours
80% Capacity	9.120 Amp-hours
50% Current Draw	22 Amps
Estimated Flight Time	0.41 hours = 24.9 minutes

Based upon specifications provided by DroneWorks for both infrared (IR) and ultrasonic sensors, two short range (~0.5- to 5-foot) and two long-range (~1- to 20-foot) sensors of each type were identified as candidates for object detection and collision avoidance. DroneWorks was to make the final sensor selection based upon both mechanical and electronic system integration considerations as well as demonstrated performance.

4.2 AVP Construction

Integrating these and other technical considerations, DroneWorks then developed a detailed design package for review to prompt additional questions, make suggestions, and identify missing information. With these modifications in place, verbal authorization was given in early May 2018 to proceed with AVP construction. Drone-Works purchased for AVP use a FLIR Vue Pro infrared camera with a wide-angle lens, 30 Hz video transmission rate, very good thermal sensitivity (~0.1 degree F), excellent image resolution, and an auto-ranging image display. Some delay was encountered due to supplier backorder for propellers, carbon tube framework assembly clamps, and motor mounts. However, all ordered mechanical parts and the FLIR camera were delivered by May 22. Custom manufacture (3D printing) of specific structural components also was completed on or about this date.

The Figures 15 through 19 represent the final proof of concept AVP custom design based on use of 11-inch diameter propellers. Figure 15 shows the lightweight but rugged carbon fiber tube construction of the central AVP airframe. Figure 16 has CAD drawings representing the complete mechanical design encasing the propellers, batteries, and on-board electronics in lightweight but crash-resistant structures. Not shown in this figure are the four propellers and an open mesh covering both the top and bottom surfaces of the aircraft to fully enclose the propellers and streamline the aircraft to minimize the possibility of it snagging on any obstructions encountered underground.

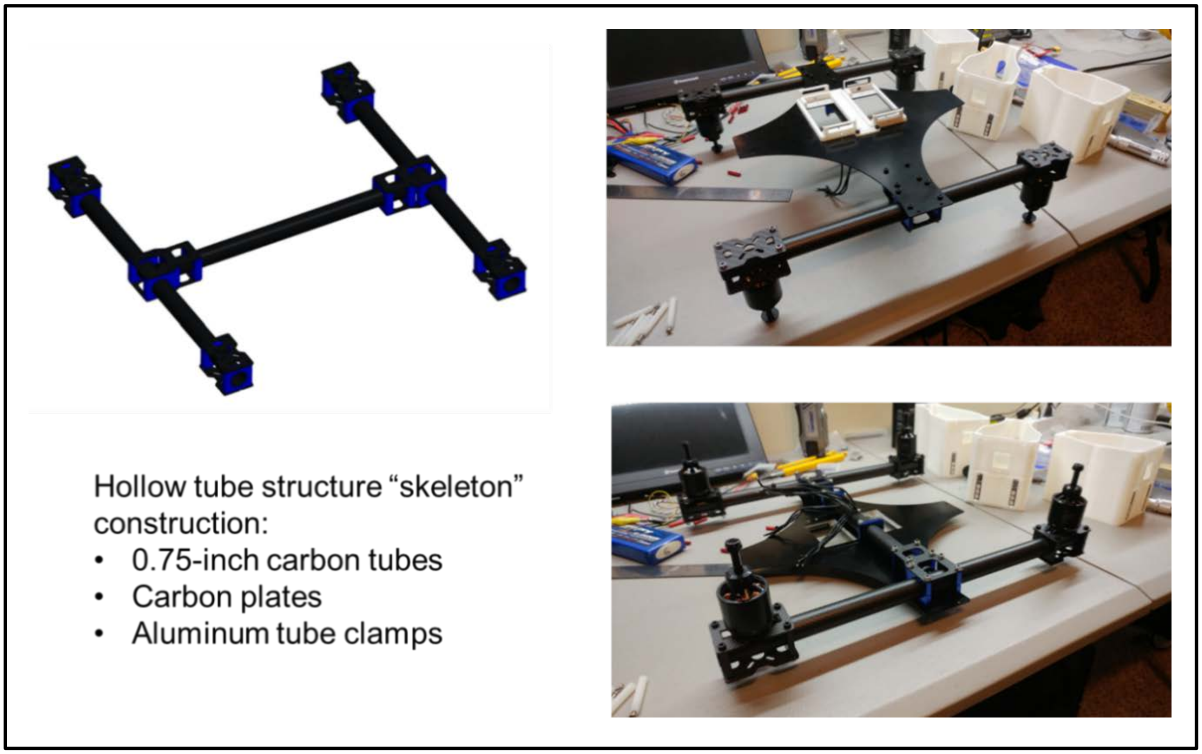


Figure 15: AVP airframe core construction

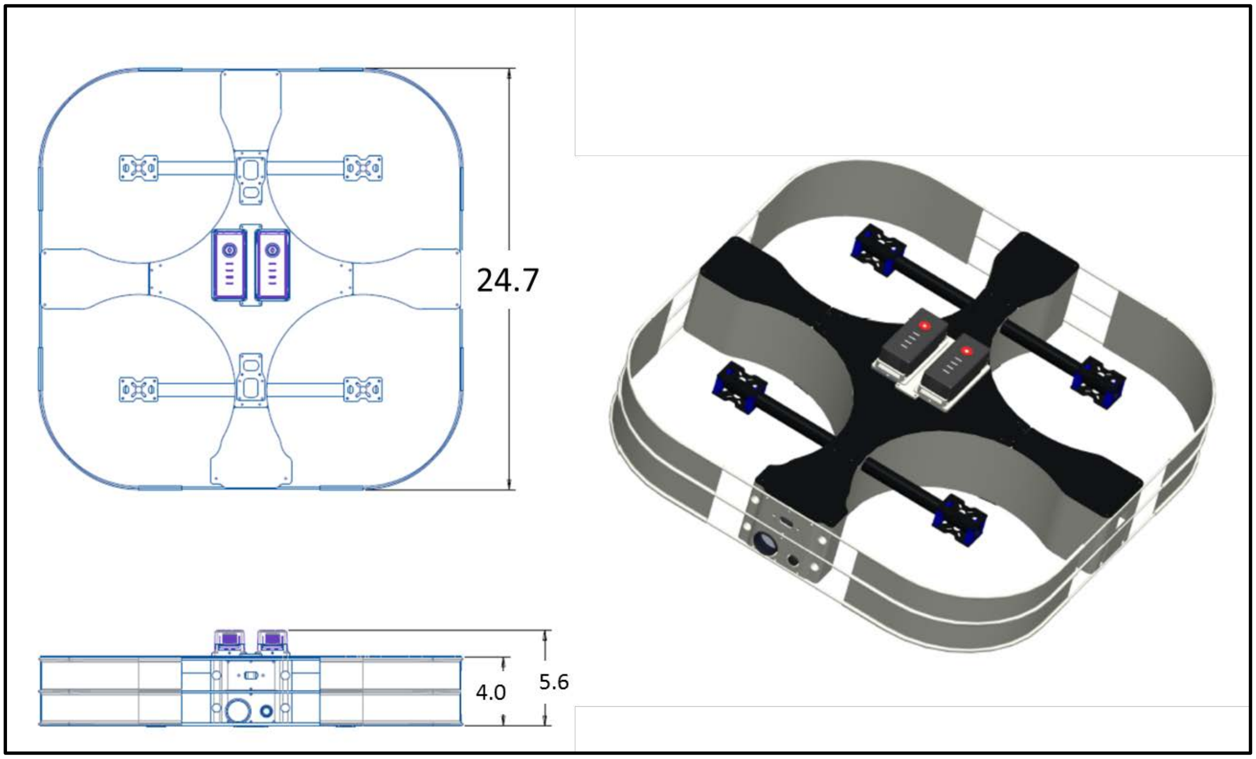


Figure 16: AVP mechanical design and overall dimensions (in inches)

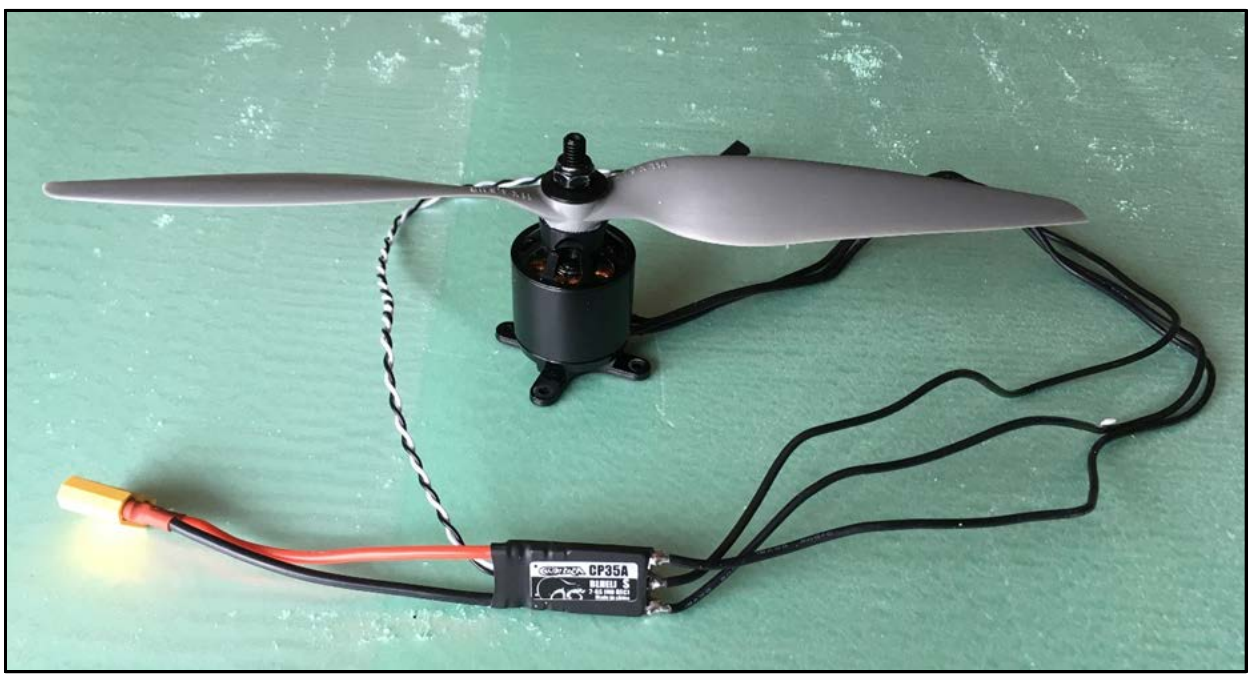


Figure 17: AVP motor with propeller and electronic speed controller

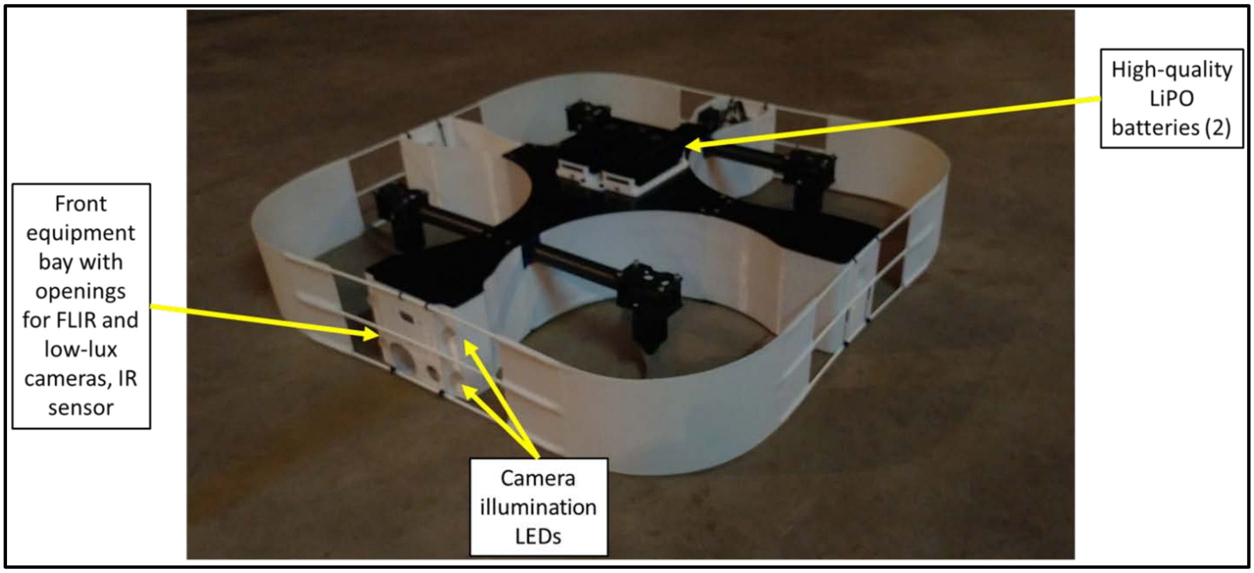


Figure 18: Assembled proof of concept AVP

Figure 19: AVP video illumination and colored navigation lighting

Figures 20 through 22 and Table 14 provide electrical information for the proof of concept AVP design.

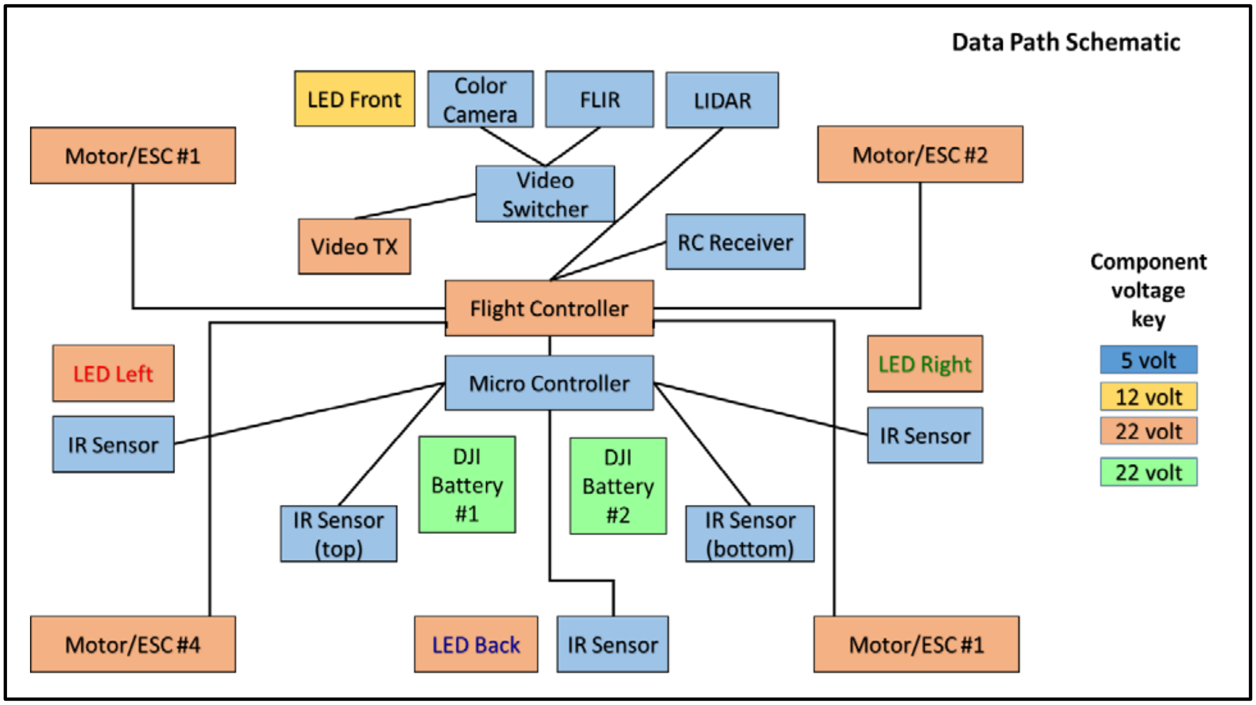


Figure 20: Data information exchange schematic diagram

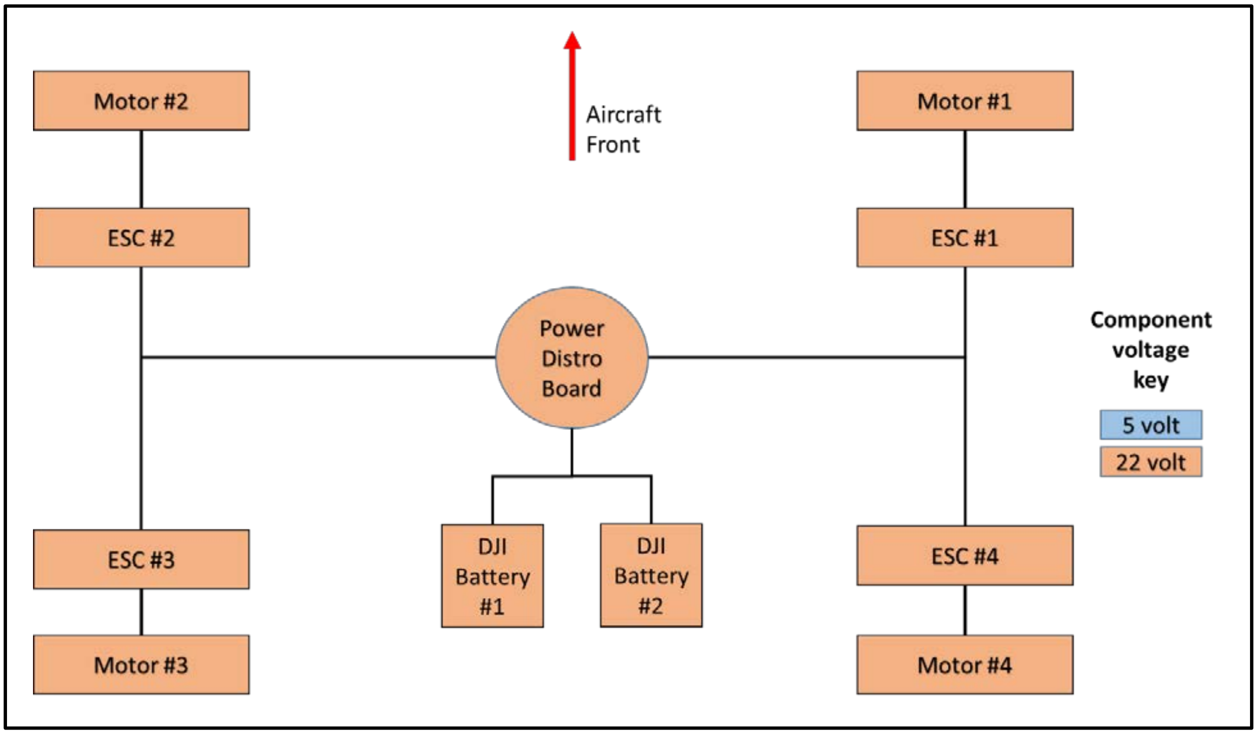


Figure 21: Power distribution to 22-volt components

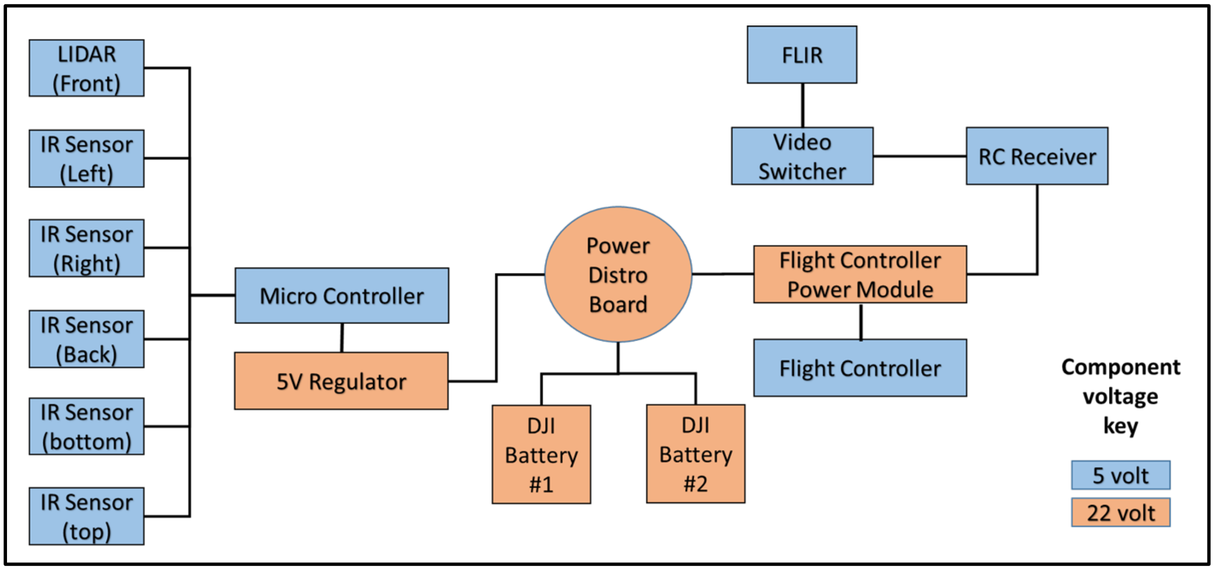


Figure 22: Power distribution to 5-volt components

Table 14: Electrical Components Inventory and Power Estimates

		Current (amps)		Power (watts)			Total Power (watts)	
Component	**Voltage**	**Nominal**	**Maximum**	**Nominal**	**Maximum**	**Quantity**	**Nominal**	**Maximum**
Motor/ESC	22.2	5.0000	35.000	111.0000	777.0000	4	444.0000	3108.0000
Flight Controller	22.2	0.0270	0.070	0.5994	1.5540	1	0.5994	1.5540
LED Front	12.0	0.1250	0.125	1.5000	1.5000	4	6.0000	6.0000
LED Right	22.2	0.0300	0.030	0.6660	0.6660	2	1.3320	1.3320
LED Back	22.2	0.0300	0.030	0.6660	0.6660	2	1.3320	1.3320
LED Left	22.2	0.0300	0.030	0.6660	0.6660	2	1.3320	1.3320
Front Sensor (IR)	5.0	0.0300	0.005	0.1500	0.0250	1	0.1500	0.0250
Right Sensor (IR)	5.0	0.0300	0.005	0.1500	0.0250	1	0.1500	0.0250
Back Sensor (IR)	5.0	0.0300	0.005	0.1500	0.0250	1	0.1500	0.0250
Left Sensor (IR)	5.0	0.0300	0.005	0.1500	0.0250	1	0.1500	0.0250
Top Sensor (IR)	5.0	0.0300	0.005	0.1500	0.0250	1	0.1500	0.0250
Bottom Sensor (IR)	5.0	0.0330	0.050	0.1650	0.2500	1	0.1650	0.2500
Microcontroller	5.0	0.0100	0.010	0.0500	0.0500	1	0.0500	0.0500
Thermal Camera (FLIR)	5.0	0.0420	0.042	0.2100	0.2100	1	0.2100	0.2100
Low Lux Video Camera	5.0	0.0200	0.020	0.1000	0.1000	1	0.1000	0.1000
Video Transmitter (max)	12.0	0.1600	0.270	1.9200	3.2400	1	1.9200	3.2400
Video Switcher	5.0	0.0100	0.010	0.0500	0.0500	1	0.0500	0.0500
RC Receiver	5.0	0.0100	0.010	0.0500	0.0500	1	0.0500	0.0500
						TOTAL	**457.89**	**3123.63**

None of the AVP design electrical components possess an IS rating issued by any certifying agency. However, the colored operating voltage and maximum current values of Table 14 associated with each of the AVP electrical components were entered into MSHA's online, interactive tool for comparison to minimum ignition curves derived [available at https://arlweb.msha.gov/TECHSUPP/ACC/application/application.htm]. While the MSHA tool is intended for application only to elementary circuits, its analysis can provide an initial, approximate indication of the level of concern posed by a system component.

For these evaluations, only MSHA's most basic, resistive power curve was employed since detailed information about internal construction and possible on-board power storage (either capacitive or inductive) for each component was not available. With the one exception noted by red fill in Table 14 (the AVP motor and its associated electronic speed controller (ESC)), the maximum power associated with all AVP components did not exceed the 90% of ignition level threshold that MSHA employs to screen and accept items without additional testing. The operating voltage and maximum currents for these components are indicated with green fill in Table 14. While neither exhaustive nor conclusive, this first level IS evaluation suggested that the power requirements of many commercially available components desirable for AVP use are within MSHA threshold limits for IS consideration.

However, it must be noted that MSHA evaluates intrinsic safety performance on an "apparatus" or "system", not "component", level. Therefore, an assemblage of IS components may not create an IS apparatus. The AVP was evaluated as an assembly of components, including the significant IS outlier component in Table 14, the AVP motor and ESC. Therefore, it was anticipated that in an initial review of the AVP design, that MSHA would focus its attention on the motors and the batteries.

Basic flight control and other primary functions, including IR and low-lux black-and-white camera image transmissions, were first tested in mid-June. Shortly after installation, the FLIR camera failed to function even when removed from the AVP and connected to the camera manufacturer's test lead necessitating its return to the manufacturer for repair.

At the same time, Drone-Works' software programmer began coding of the secondary flight control using the sensor inputs for collision avoidance to over-ride operator control when obstacles are detected. While the AVP secondary flight control algorithms are similar to algorithms previously developed by DroneWorks for a prior application, implementation and testing of the sensor fusion required more time than originally estimated.

At this point in overall project execution, significant schedule delays had accumulated from:

- delayed material deliveries resulting in AVP construction delays by DroneWorks
- failure of the FLIR camera,
- additional time required for secondary flight control implementation

Therefore, a request to extend the research period of performance two months until September 30, 2018 was submitted to the Alpha Foundation on June 28, 2018. This request was approved on July 3, 2018.

4.3 AVP Flight Stability

The initial test of the AVP secondary flight control by DroneWorks in early July exhibited poor results with unstable AVP flight when using initial control settings adapted from the prior application. This performance mandated additional tuning of the AVP's proportional, integral, and derivative (PID) programmable logic controllers and checking the configuration of the four individual motor speed controllers. Evaluation of subsequent test flights revealed two significant problems:

1. The six ultrasonic sensors installed for up, down, left, right, and rear object detection and collision avoidance didn't function effectively in an enclosed space due to their close mutual proximity and resulting cross-talk among the sensors, even when applying a "daisy chain" activation method suggested by the manufacturer to address this potential issue.
2. AVP flight behavior was not as stable as anticipated with respect to eliminating a persistent "yaw" (horizontal rotation) instability for which the cause was not immediately evident.

Based upon these observations, DroneWorks recommended substituting infrared (IR) sensors for the five ultrasonic sensors and investigation of possible electronic speed controller (ESC) and motor incompatibility as one cause of the flight stability issue.

Subsequent investigation revealed that the AVP unstable yaw problem apparently originated from a non-linear response by the installed motors to applied electrical power. Because of the substantial weight of the AVP (nearly seven pounds) and its use of large diameter (11-inch) propellers, the motors had to turn at a high rate near their upper design range for the AVP to hover. Below the hovering rate, the motor response to applied power was approximately linear and well behaved. AVP flight was stable when simply hovering. However, just above the hovering rate, motor response became highly non-linear and RPM (and propeller torque) increased very rapidly when only slightly more power was applied. This behavior was not recognized during the motor bench test performance evaluations conducted in April 2018. Therefore, as additional power was applied to the different motors to enable flight maneuvers, unanticipated RPM imbalances occurred rapidly for which the onboard flight controller could not compensate. The resulting unbalanced propeller torques caused the observed yaw instability.

While the proof of concept AVP was flyable, it required constant observation and pilot intervention for well-controlled flight. While this might be possible by an experienced pilot while directly observing the AVP, it would be more difficult for a less experienced pilot to maintain stable flight. However, of greater concern, successful extended flight in a dark enclosed space using only a transmitted camera image would be extremely challenging for a pilot of any skill level.

Near the end of July 2018, DroneWorks offered two options to address the AVP inherent yaw issue:

1. Investigate and evaluate other comparable motors to identify another motor which possessed better response in the RPM range required for AVP operation. If a suitable replacement could be identified, make that substitution. DroneWorks was aware of only one other motor with characteristics similar to the installed model, and its higher RPM behavior was unknown. The motor investigation process could not be completed and still maintain the project schedule extended at the very beginning of July. More critically, there was no guarantee that this investigation would reveal a close replacement that would enable continued use of the existing custom-designed AVP airframe.
2. Substitute a different, proven airframe and motor combination as a surrogate for the custom-designed AVP airframe built by DroneWorks. The basic TBS Discovery airframe (Figure 23) possessed many attributes necessary for the AVP flight demonstration except for having protection for the propellers. DroneWorks had identified a source capable of rapid delivery of the needed components. DroneWorks would custom design and 3D print necessary propeller guards for the TBS Discovery. Substitution of this alternative airframe that had inherent flight stability would incur only minimal additional schedule delay.

Figure 23: Generic commercial TBS Discovery asymmetric quadcopter airframe

Following discussion of both options, DroneWorks, was instructed to aggressively pursue the second option with the provision that they also deliver the unstable AVP for static demonstration purposes.

While the TBS Discovery airframe may be rugged and has a reasonable flight endurance, its basic design is definitely not well suited for underground use. Therefore, functional flight demonstrations to evaluate aircraft communication, on-board camera performance, and guidance sensor integration would be executed by the TBS Discovery while the purpose-built but non-powered AVP would be used to demonstrate a more mine-worthy design better suited for a prototype AVP airframe. As originally planned, display of the AVP would support engagement and IS discussions with personnel at the MSHA Approval and Certification Center.

During August 2018, the basic components for the TBS Discovery airframe were purchased and the assembled aircraft was modified for capability and performance demonstration of flight control and mission function in an enclosed space. The malfunctioning FLIR camera was repaired by FLIR and returned. Figure 24 shows the basic TBS Discovery airframe after modification with forward-facing and upward-oriented IR sensors mounted in a custom-designed (black) dorsal enclosure mounted above the intersection of the aircraft's four rotor arms. The dorsal enclosure also housed the other horizontally oriented IR sensors pairs. The downward-oriented IR sensor pair was mounted beneath the airframe. The low-lux visible light and FLIR cameras were mounted in a (white), front-facing enclosure. Custom fabricated (white) propeller guards were also applied to protect the aircraft's four propellers. The programing of the sensor outputs to override operator flight control command and thus effect collision avoidance was transferred from the custom-designed AVP to the TBS Discovery and function tested.

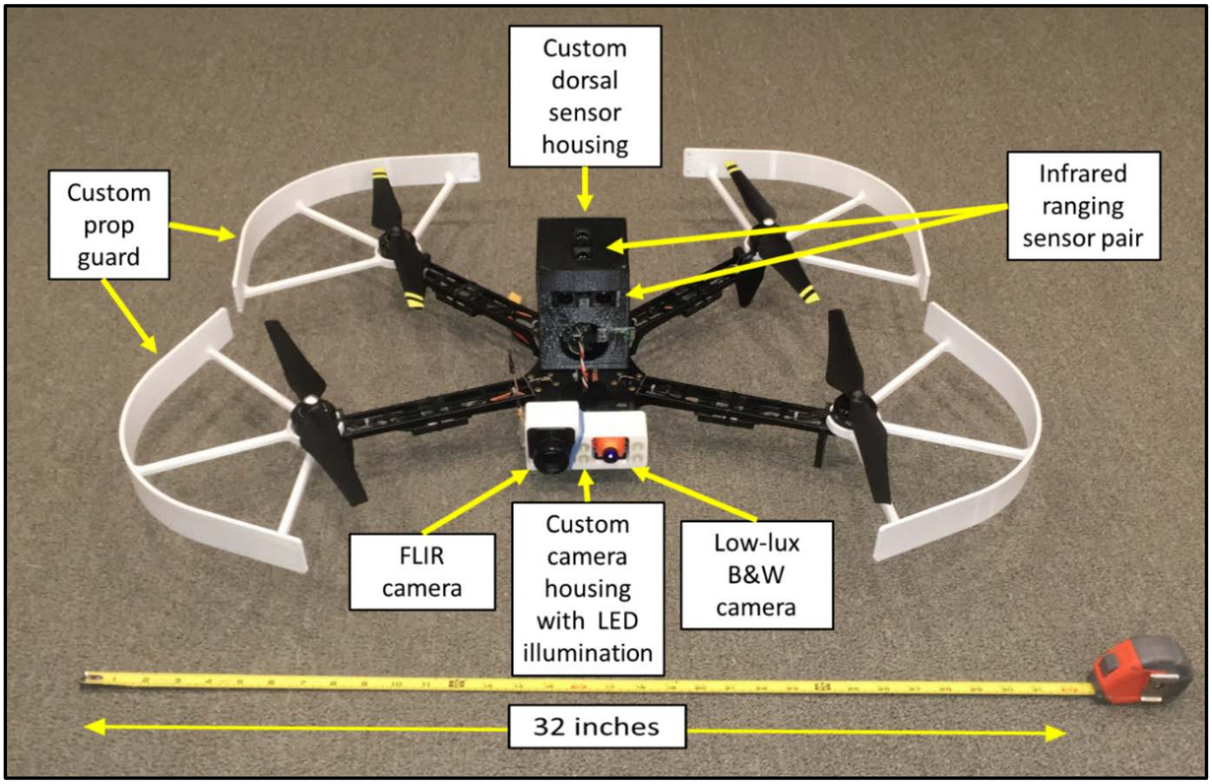


Figure 24: Modified TBS Discovery airframe with custom components attached

Installation of the four custom propeller guards (each with a mass of 88 grams), the dorsal IR sensor housing (350 grams), the FLIR camera (115 grams), the low-lux camera (15 grams), and the custom camera enclosure (150 grams), provided a total of 982 grams (0.982 kilograms) of payload added to the basic TBS Discovery airframe. By early September 2018, preparation of the TBS Discovery airframe was complete and its delivery by DroneWorks (along with the non-powered custom-designed AVP airframe) and functional demonstrations were conducted the weekend of September 8-9, 2018.

5.0 Proof of Concept Evaluation

All AVP proof of concept performance criteria are presented in the "Mission Requirements and Evaluation Protocol Matrix" of Table 12.

Note that three of the Mission Requirements were to be verified by "Inspection". These include AVP-2 (Maximum Dimension), AVP-6 (Rotor Enclosure), and AVP-8 (Hazardous Area Operation).

While the maximum dimension of the purpose-built AVP design at 24.7 inches (Figure 16) is less than the 30-inch AVP-2 requirement, the surrogate TBS Discovery asymmetric quadcopter airframe had a width of 32 inches (Figure 24) across its front propellers due to the addition of custom propeller guards necessary for safe enclosed space operation and to address AVP-6. The purpose-designed, mine-worthy AVP provided more resilient, full enclosure for its propellers.

Mission Requirement AVP-8 has been mentioned briefly in Section 4.2. There it was noted that none of the components used to construct the custom-designed AVP possessed an IS approval. However, with the exception of the motors and their electronic speed controllers, the potential maximum power individually needed by all electrical components appears to be less than the power levels that MSHA initially considers to be a concern for simple resistive circuits. This topic is discussed in greater detail in Section 5.2.

The remaining seven Mission Requirements of Table 12 were to be verified through "Demonstration" using the indicated method associated with each to guide execution of flight-testing, originally intended for the purpose-designed AVP but actually conducted with its surrogate, the modified TBS Discovery airframe.

Additional confined space flight-testing also demonstrated the ability to successfully control and maneuver UAVs in mine-like settings from a distant remote location, a key operational requirement for AVP use in mine rescue support. In addition to the TBS Discovery, two other, smaller airframes (a Parrot Bebop 2 and a DJI Mavic Pro) were flown in confined spaces to gain flight experience and a better understanding of the associated challenges the performance of available technologies to enable successful operation.

The following sections first present evaluation of the AVP and TBS Discovery proof of concept demonstrators followed by flight performance observations made with commercially available drones.

5.1 Project Flight Testing and Performance Evaluation

5.1.1 September 8, 2018 Tests

On September 8, 2018, DroneWorks personnel affixed the FLIR/low-lux black-and-white camera pod and prop guards (see Figure 24) to the TBS Discovery airframe prior to general flight function testing.

Airframe flight was controlled using an Fr SKY-TARANIS X9D transmitter (Figure 32) with its control functions custom programmed for use with the TBS Discovery. An Immersion RC Uno5800 V4.1 receiver captured video transmission from the aircraft, and the received signals were displayed on a 19-inch diagonal flat screen television.

Figure 25: Fr SKY-TARANIS X9D transmitter

Open-air tests demonstrated video signal transmission from the drone to a flat screen television and the ability of the TBS Discovery to maintain a nearly constant altitude, which could be adjusted on the handheld flight controller. Per requirement AVP-9 (Obstacle Sensing), the TBS Discovery also appeared to automatically avoid obstacles that came within a range of less than 2 feet from all horizontal directions and above. One "hard" landing was observed when the TBS Discovery was instructed to land using the handheld Fr SKY-TARANIS X9D transmitter.

Per requirements for AVP-4 (Operational Range) and AVP-5 (Flight Duration), flight endurance and control range testing demonstrated continuous open-air flight for 13.8 minutes at a measured communication range of 1,120 feet while carrying its additional payload mass of 982 grams. It is possible that if the TBS Discovery was kept hovering without any significant acceleration and maneuvering, the measured flight time could have extended to between 14 and 15 minutes. The AVP flight duration minimum objective was 20 minutes. Both black and white low-lux video and FLIR IR image transmission to the television was also demonstrated at a range over 1,000 feet, also achieving the AVP-4 requirement. Some intermittent signal/image dropout was noted depending upon the azimuth of the TBS Discovery transmitter relative to the directional antenna employed by the video receiver to capture signals for the television.

5.1.2 September 9, 2018 Tests

The purpose of flight tests conducted on September 9, 2018 was to fully evaluate the integrated performance of the following sensors and custom flight guidance software on the TBS Discovery airframe:

- 1 low-lux visible light black-and-white camera
- 1 FLIR infrared (IR) camera
- 1 video signal transmitter
- 1 downward looking, shorter-range (0.1- to 1.5-meter) detection IR sensor pair
- 5 longer-range (1- to 5-meter) detection IR sensor pairs (facing forward, up, left, right, and to the rear)

Flights were conducted in the dark basement of an industrial building for which a plan view diagram is provided in Figure 26. As noted on the plan drawing, plastic tarps were suspended from ceiling structures to the floor in a manner to (1) approximate the widths of entries in the mine simulators where the TBS Discovery could be demonstrated, (2) provide conditions to demonstrate aircraft function and maneuverability, and (3) offer a controlled environment for operator training. The colored dots in Figure 33 indicate both the take-off sites and locations where major aircraft flight problems or crashes occurred.

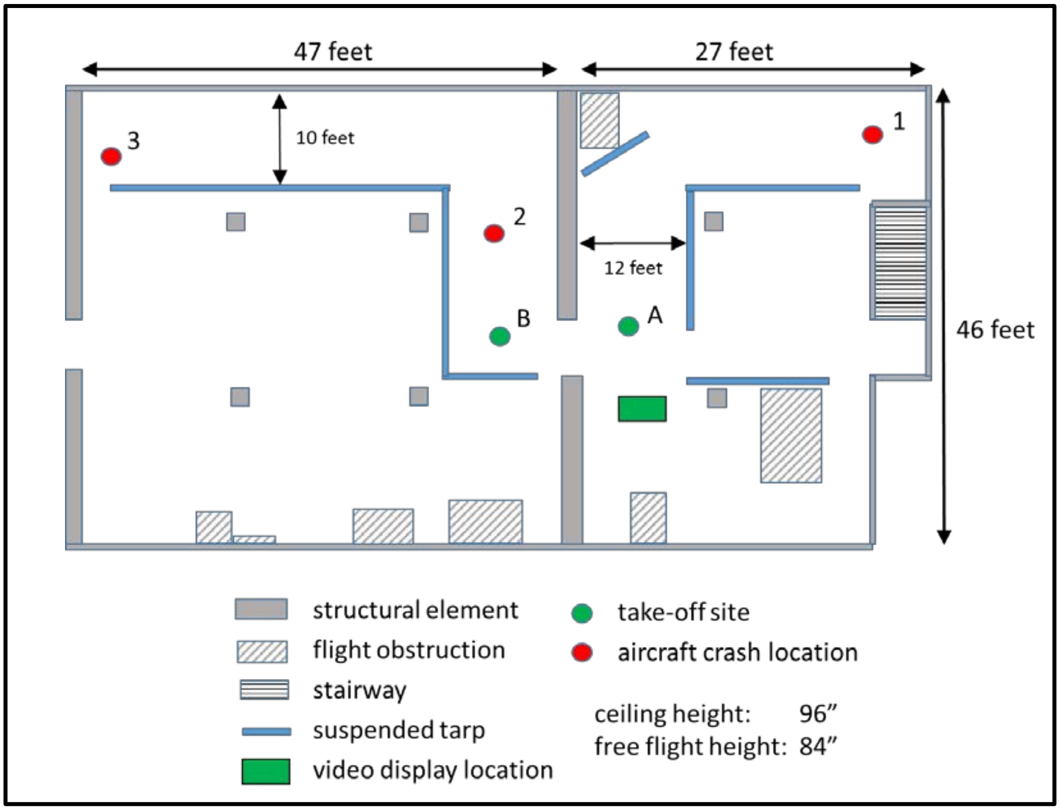


Figure 26: Plan view sketch of the of 9/9/18 confined space flight test site

5.1.2.1 Performance Observations

Vertical flight stability: IR sensor response and flight controller programming were designed to automatically control the flight height above the floor and prevent the aircraft from coming in contact with the roof. The operator could adjust flight height between approximately one and four feet above the floor rotating a switch on the Fr SKY-TARANIS X9D transmitter. If the roof height decreased, the program would cause the set flight height to decrease to maintain a minimum distance from the roof, if possible.

The modified TBS Discovery airframe demonstrated automatic take-off and level flight at a fixed, stable height above the floor. Flight height and overall airframe stability improved with greater height above the floor as “ground effect” turbulence decreased. As noted during the open-air tests of September 8, 2018, the IR sensors on the TBS Discovery again interacted with the on-board flight controller in a manner such that it generally avoided the basement ceiling and large objects they detected in the horizontal plane, as long as the rate of closure to those objects was relatively slow. Thus, requirement AVP-10 (Centering Flight Mode) was demonstrated in an enclosed environment.

The first flight incident resulting in a crash occurred after a take-off from site A. For reasons not completely understood, the aircraft closely approached within approximately 18 inches of the solid ceiling near the corner of the basement indicated with red dot number 1 in Figure 33 and then collided with an unpowered fluorescent light fixture. Subsequent inspection of the functional response of the upward looking IR sensor suggested a temporary sensor malfunction or loss of data might have allowed the aircraft to rise rather quickly to an unexpected and undesirable height.

Prop guards broken by this collision and subsequent 7-foot drop to the cement basement floor were either repaired or replaced so flight-testing could continue. Note that although this occurrence was not planned, it served to address requirement AVP-7 (Crash Resistance) as the main airframe did not suffer any structural damage nor were any of its primary electronic components damaged or exposed because of this crash.

Horizontal flight stability (centering, obstacle avoidance): Sensor response and flight control programming in the horizontal directions were set to approximately center the aircraft in the simulated mine entry opening while prohibiting approach to detected objects closer than about 2 feet from the sensor. However, as noted above, it was observed that it was apparently possible to over-run the collision avoidance sensor settings if the aircraft approach speed was sufficiently great so the program did not have time to intervene and respond effectively. "Ground effect" turbulence also seemed to play a role in degrading horizontal stability in that the aircraft could not automatically maintain a fixed position within either 10- or 12-foot wide simulated mine entries without some operator manual control intervention.

Hard landing: To initiate aircraft take-off, one toggle switch at the front left corner of the Fr SKY-TARANIS X9D is flipped up. The propellers begin to spin and the aircraft then ascends to the selected hovering height above the floor. To land the aircraft, the toggle switch is flipped down, and the aircraft is supposed to slowly descend to the floor as the propeller rotational speed gradually decreases.

In at least one instance when the aircraft received the command to land, the propellers' rotation very briefly increased causing a slight increase in altitude followed by a very abrupt decrease in speed resulting in a "hard" landing. This same phenomenon was noted once during initial, open-air flight tests conducted on September 8, 2018. This appears to be an occasional but not constant behavior.

The impact of this "hard" landing (which occurred at the number 2 site indicated on Figure 33) caused failure of a repaired joint on one of the prop guards damaged in the prior crash. The damaged prop guard was again repaired and testing continued.

Aerodynamics of operation in an enclosed space: An extended flight test (which started at take-off site B) ended abruptly with a catastrophic crash that occurred at the left end of the longest simulated mine entry, as indicated in Figure 26 by red dot number 3. The aircraft had been flown from near the doorway separating the two major basement areas, had successfully negotiated a left-hand turn, and had proceeded to the end of the simulated mine entry. These operations (and others conducted earlier), satisfied mission requirement AVP-1 (Maneuverability). As the aircraft was rotated 180 degrees to retrace its path, it very suddenly flipped over around a horizontal axis of rotation and crashed, shattering or severely damaging all four prop guards, breaking two propellers, and cracking the exposed dorsal mounted IR sensor enclosure. Since no more prop guards were available, this crash ended the execution of the flight test program.

Based upon the facts that (1) flight control had been relatively stable up to this point and (2) no unusual operator instructions were being provided to the aircraft at the time of the crash, it was theorized that a sudden loss of regular, uniform airflow around the aircraft might be the root cause for this crash. Unequal, and therefore unbalanced, downward thrust for propellers on opposite sides of the aircraft would cause the observed aircraft rotation. The 11-inch propellers employed by the TBS Discovery move large volumes of air. If the TBS Discovery was flown near a wall or in a corner, air might not flow uniformly. If a constant air supply were not maintained, a very rapid thrust imbalance could result.

Interruption to video transmission display: Although it did not appear to be a critical issue during these flight tests, it was noted that the video signal displayed on the television was not continuous. The display suffered from brief interruptions that during these flight tests proved to be at first unnerving and then only annoying. However, this annoyance would become a major problem if they became prolonged or occurred frequently when the video feed was the only means used to monitor aircraft performance in real time.

5.1.2.2 Action Items

DroneWorks was tasked to repair the TBS Discovery demonstration airframe that was damaged to its original pre-testing physical condition. Then develop and implement improved performance of its secondary collision avoidance programming prior to any further flight demonstrations. As the platform that possesses all basic AVP sensor functions, the TBS Discovery must be flight worthy to be employed as the primary technology demonstrator.

Therefore, the following tasks for DroneWorks were defined:

- Task 1: Fabricate a new complete set of prop guards and a complete set of spares.
- Task 2: Repair the damaged central IR sensor housing.
- Task 3: Function test and repair as necessary all mechanical and electrical systems.
- Task 4: Develop software modifications as necessary to make vertical flight control more robust, reconcile entry centering, and lateral collision avoidance control conflicts.
- Task 5: Install software modifications
- Task 6: Fully test and evaluate all new software modifications.
- Task 7: Procure additional spare parts as prudent, including a third battery pack and dedicated battery charger

5.2 September 19, 2018 MSHA Meeting

To authoritatively ascertain Mission Requirement AVP-8 (Hazardous Area Operation) status, an informal technical meeting was requested to obtain an initial assessment by MSHA Approval and Certification Center (A&CC) personnel of intrinsic safety issues and concerns related to the more mine-worthy AVP design. Having the design specifics of Section 4.2 on hand along with their physical embodiment facilitated the meeting discussion as these provided focus for mutual exchange related to issues that the A&CC personnel had not previously encountered. This level of meeting preparation also fostered a positive impression of the project and its objectives by the A&CC personnel.

5.2.1 Discussion Topics

AVP Project Motivation, Objective, and Activity (to date): An 11-page handout, "AVP Design Concept and Construction", was distributed to all participants. This handout, the original custom-built AVP airframe, and some if the airframe's key spare parts (motor and associated electronic speed controller (ESC), three different 11-inch propeller styles) were used to present and summarize the process employed to design the proof of concept AVP (see previous Section 4.1). In addition, some key lessons learned from AVP (previous Section 5.2) and other platform flight tests in confined spaces (following Section 5.3) were shared. It was noted that perhaps the primary lesson learned to date was that a smaller airframe would have a greater chance of success for the intended application, even if some initial performance requirements have to be scaled back or even sacrificed.

Battery Power Concerns: A&CC looks to Underwriters Laboratory (UL) certification to the UL1642 standard as a means to initially qualify battery technology and construction. If a specific battery has passed the UL 1642 crush and short-circuit tests, then A&CC is confident it would also pass their testing regimens. Most often, only individual single cells are evaluated and receive UL certification. Batteries made of multiple cells may not be UL certified. A&CC also considers any limitations on "conditions of use" associated with a UL certification to insure that the proposed mining application complies with the approved use conditions.

Many lithium polymer (LiPo) battery packs have sophisticated electronics included to detect the charge state and health of individual cells and prevent potential cell damage due to over-charging or battery explosion due to charging a damaged cell. The DJI Matrice 100 TB48D battery proposed for use in the original AVP design has such electronic protection. A&CC would also need to evaluate those monitoring and protection circuits during their IS evaluation. Therefore, it may be more straightforward from an IS approval standpoint to employ less sophisticated power supplies that do not possess integrated protection devices.

The A&CC personnel also noted that battery charging is an overall safety concern and the location, method, and physical protection provided by a charging station must be considered in any operational scenario. Also, battery replacement in a fresh air environment is highly recommended, if not mandatory, because of the greater potential for electrical sparking as batteries are disconnected and connected.

In general for initial IS considerations, A&CC prefers operating voltages in the 10-volt range. Their level of concern increases when a system operating voltage exceeds 12 volts. The output from batteries supplying even these voltages must then be current limited to keep any inadvertent energy release less than that necessary to ignite an explosive atmosphere. MSHA's website [https://arlweb.msha.gov/TECHSUPP/ACC/application/application.htm] has an interactive tool to evaluate ignition limits for different voltage and current combinations.

Motor Concerns: Although brushless motors employed in most drones are "non-sparking", they may draw large currents and possess significance inductance which can represent stored energy. As possible, motor operating voltage and currents should be minimized. A&CC also has developed a tool to evaluate motor inductance (L) and current (I) relative to IS ignition limits. The curves calculate the product ($0.5*L*I^2$) as the basis for evaluation. Therefore, motors operating at lower currents may be better suited for the AVP application, from a purely IS perspective.

Motors also have to be evaluated under fault conditions such propeller rotation stoppage (stalling) and potential failures resulting in internal physical damage.

Commercial Off-the-Shelf (COTS) Components: Using COTS components can often be problematic due to the need for MSHA to know the detailed design of those components which many, if not most, companies consider to be their proprietary information. There are ways to address the confidentiality issue, if the manufacturer is willing to cooperate. However, this can be a time-consuming process and an applicant runs the risk of voiding an issued approval if the COTS component manufacturer subsequently alters or no longer produces a component employed as an element of an approved item.

FLIR Camera: The A&CC personnel have had past interactions with FLIR related to underground use of some of their products. Specific product types or models were not discussed. The products A&CC has investigated employed voltages and currents which elevated them above MSHA inherent IS standards. Enclosing an infrared camera in an explosion-proof (XP) enclosure is problematic due to the need to have an IR-transparent window in the enclosure. Transparent materials commonly employed in XP enclosure construction are not IR-transparent. IR-transparent materials of which the A&CC personnel are aware are both costly and too brittle for use in an XP enclosure. NOTE: A&CC personnel were not asked if the small FLIR cameras suitable for AVP use with their low power requirements (indicated in Table 14) might better approach or align with inherent IS requirements.

Component Surface Temperature: The A&CC personnel noted that surface temperature of all exposed components must remain under the ignition temperature for an explosive atmosphere (85 degrees Centigrade or 176 degrees Fahrenheit) under both normal and abnormal operating conditions. As one example, operating temperature of some high-intensity LEDs may be a concern.

Static Electricity Discharge: Although MSHA does not have a specific protocol to evaluate equipment for potential static buildup and discharge, A&CC personnel did raise this concern about the spinning AVP propellers. They noted that carbon fiber propeller blades may be prone to static charge accumulation under certain flight conditions. For the 11-inch propellers employed on the original AVP design, a slightly less efficient wooden blade option was presented which was apparently well received, as wood is not known to accumulate static charge.

Encapsulation as an Acceptable IS Technique: Per MSHA guidelines presented in document ACRI2001 [https://arlweb.msha.gov/techsupp/acc/application/acri2010.pdf], component encapsulation is allowed as a method to isolate electrical components from an explosive atmosphere. However, this is not approved as a stand-alone technique for some applications.

A&CC does not approve specific compounds for use in encapsulation. The effectiveness of any application proposing encapsulation is always evaluated as an "assembly" which allows A&CC to observe how a potting compound or other substance promoted for encapsulation interacts with the other materials with which it is in contact. The entire "assembly" is subjected to both extreme heat (170 degrees Celsius or 338 degrees Fahrenheit) and cold (-20 degrees Celsius or -4 degrees Fahrenheit) to detect any adverse effects of thermal expansion and/or contraction on the physical integrity of the "assembly" that could expose components to a hazardous outside atmosphere. The "assembly" is also subjected to a drop test immediately after being subjected to the extreme cold conditions to demonstrate that "assembly" elements do not become so brittle as to compromise their atmospheric isolation characteristics. Another requirement for encapsulation is that no voids are allowed within the encapsulating material.

The concept of isolating the AVP motors from the ambient operating atmosphere by employing a sealed protective housing that transmits motor rotation to the propellers through a magnetic coupling was discussed. A&CC personnel had not previously considered this possibility. Their initial reaction was that since motor operation within the housing would require the presence of a void space, this approach could not be considered as "encapsulation". The safety performance of the sealed housing would then have to be evaluated as an XP enclosure.

5.2.2 Suggested Action Items

A&CC personnel offered to again meet informally to provide insights and guidance related to future AVP development. They also offered the following suggestions which might serve to expedite that development:

AVP Redesign: To approach and possibly achieve an AVP design capable of MSHA approval for use in hazardous underground environments, it may be necessary to initiate the AVP design process with a first focus on intrinsic safety requirement considerations. The remaining SME-suggested performance requirements would then be addressed as possible within the IS-imposed constraints. The specific suggestion was that the design process should start at the power supply (battery) and then examine what commercial motors might successfully operate with current and voltages limited by IS requirements. Candidate COTS motors would probably need to offer a high RPM per volt rating.

As one specific example, Koehler sells a lithium-based battery pack [PTO Battery LI-5000-AR1, http://www.flashlight.com/wp-content/uploads/2012/01/Koehler5300_SellSheet.pdf] that has received a stand-alone MSHA approval which might serve as a design starting point.

Investigate Other Agency Approvals: Explore IECeX.com to identify components or devices that have been successfully evaluated by the International Electrotechnical Commission (IEC). Additional background information is available from IEC publication 60079-11:2011 [https://webstore.iec.ch/publication/626] that specifies the construction and testing of intrinsically safe apparatus intended for use in an explosive atmosphere and for associated apparatus, which is intended for connection to intrinsically safe circuits which enter such atmospheres.

5.3 Flight observations conducted with COTS drones

While the custom-designed AVP airframe was under development, two different commercial-off-the-shelf (COTS) drones were acquired to enable flight practice in simulated mining environments and provide operational learning experience from their performance. The UMWACC Simulated Mine was the primary site employed for these exercises.

5.3.1 Parrot Bebop 2 Observations

The basic Parrot Bebop 2 (Figure 27) is a smaller quadcopter than either the custom-designed AVP or the modified TBS Discovery. Its maximum dimension is 13 inches, it weighs 1.1 pounds, and it employs 6-inch propellers. The drone can be flown remotely using onboard camera images displayed either on a mobile phone or through a First-Person View (FPV) visor worn by the pilot. The FPV displays offer the drone pilot the sensation of being aboard the drone. The Bebop 2 does not possess a collision avoidance system.

Figure 27: Parrot Bebop 2 quadcopter

In late January 2018, initial test flights were conducted using an unmodified Parrot Bebop 2 in the UMWACC simulated mine. The following were the key observations:

- Since the drone did not have an integrated light source, a 350-lumen supplemental light source was temporarily attached to assist in flying in the darkness of the simulated mine.
- The propellers were capable of stirring up and circulating substantial amounts of limestone dust from the simulated mine floor, occasionally obscuring the drone's camera.
- Take off position had to be well above the mine floor to minimize creation of a dust cloud.
- The lack of discernable landmarks or reference points in the simulated mine made it difficult to perceive drone movement when using either the mobile phone image or the immersive FPV unit.
- Landing at a distance when directly observing the drone was difficult because of a lack of depth perception. It was observed that the pilot could get the Bebop 2 close to the desired landing site. It was thought that with more experience, a pilot would perfect this maneuver.
- Flying the drone around the corner of a simulated pillar without the pilot having a direct line of sight was, at best, difficult. Further testing and additional pilot experience was recommended.

During April 2018, additional tests flights were conducted in the UMWACC simulated mine to determine if the quadcopter could be flown the length of an entry outside of the operator's direct line-of-sight. Use of the First-Person View (FPV) visor was eliminated. Use of a large 27-inch monitor dramatically improved the resolution of the live image from the quadcopter.

During the flying sessions, successful exploration of a mine entry was accomplished. Furthermore, the operator was able to turn the quadcopter around at a distant position in the entry and return to the take-off point. During the final flight, the operator successfully flew the quadcopter around the corner of a pillar in the first entry and into a crosscut. He then explored the cross-cut through to the third entry before losing communication with the quadcopter.

The following observations resulted from the April test flights:

- The addition of the external 350-lumen light source to the quadcopter affected the quadcopter's ability to remain stationary while hovering and impacted straight-line flying. Once the best location for the light source was established, the problem was resolved to a level that enabled reasonable flight control in the mine simulator.
- Introduction of a properly mounted infrared camera or a low-lux camera and an associated built-in light source was determined as a critical need for successful in-mine flight.
- Low-profile reflectors hung from the mine roof greatly facilitated navigation through the mine openings as the ribs and roof of the simulated mine are painted black and possess few discernable, distinguishing landmarks.

- Once communication with the quadcopter was lost, the unit typically flew uncontrollably into a rib and crashed. It appears that once communication is lost, it may be impossible to reestablish communication before the quadcopter crashes. Recovering the quadcopter once it crashes could present problems. An effective automatic power-down cycle must be designed in the event that the quadcopter must be left in place for the mine rescue team to later recover.
- If the quadcopter crashes, the unit must land in an upright position to permit subsequent takeoff and flight. Hard crashes damaged the prop guards and a prop during test flights. This level of damage would preclude any follow-up takeoff.

Additional pilot training was conducted in May 2018 in both the UMWACC Simulated Mine facility and the West Virginia University (WVU) Academy for Mine Training and Energy Technologies mine simulator located near Core, WV. The purpose of these training exercises was to develop further understanding and gain experience flying in mine-representative environments. All flying exercises were conducted with either the Parrot Skycontroller 2 and an iPad or the Skycontroller 2 with the Parrot FPV Cockpit glasses for pilot control and ground visualization.

During the UMWACC flight exercises, it was observed that the drone intermittently but preferentially flew in a reverse direction as if receiving a conflicting radio frequency signal. At times, forward flight was nearly impossible. When the drone was flown outside of the simulated mine, the problem did not occur. When forward flight was possible in the simulated mine, flight guidance experiments using hanging low-profile reflective guideposts and light sticks on the mine floor proved very useful for navigation. Because of the reverse flying issue, attempts to turn and fly in a crosscut were difficult. Various lighting configurations on the drone were attempted to try to minimize the reverse flying problem, but none eliminated the problem. It was also observed that without warning the drone would intermittently tightly spiral downward out-of-control and eventually crash. Again, this problem was attributed to receiving a conflicting radio frequency signal or other cause for losing signal contact with the Skycontroller.

Flight conditions at the WVU facility were similarly set-up using the hanging reflectors on the mine’s lifeline and chemical light sticks placed on the mine floor. Various supplemental lights were affixed to the drone to try to determine if the drone needed to view the ground immediately below the drone for forward flight. This did not eliminate the problem of flying in a reverse direction. Again, when the drone was flown outside of the WVU simulated mine, this problem did not occur, as similarly observed at the UMWACC.

A second Bebop 2 unit was then tested that had not been flown previously in a simulated mine. In this case, the drone was flown using a Parrot Skycontroller 2 and an iPhone. Using the second Bebop 2 and the flight control configuration, the pilot was able fly the drone the entire length of the facility, into a crosscut and back out. The pilot was also able to fly the drone to the next two crosscuts, turn the drone to look into the crosscut and turn again and move forward to the next crosscut. However, during certain flights, the drone would periodically spiral downward out-of-control. In some instances, the pilot could regain control and in others, the drone eventually crashed. This condition was again attributed to a temporary loss signal. When the drone was flown outside of the simulated mine, the problem was observed only once, and the drone crashed. It is unknown why this happened. Perhaps it was due to a temporary signal loss.

The following items were either learned or reconfirmed from the flights at both facilities:

- Powerful LED lights are needed to enable flight if using a standard visible light camera to navigate.
- Chemical light sticks on the mine floor and reflectors on the mine roof greatly aid in navigation along the flight path.
- Radio frequency interruption or temporary signal loss can easily lead to a drone crash. It is not clear which condition caused the loss of pilot control. It is also thought that the metal structure in the simulated mine facilities may be causing some of the observed problems.

5.3.2 DJI Mavic Pro Observations

Recognizing that the Parrot Bebop 2 drone possessed some significant inherent limitations interfering with its performance in the simulated mine environments, a more sophisticated DJI Mavic Pro drone was purchased in July 2018 for additional flight-testing and operator training. The Mavic Pro (see Figure 28) has a high degree of flight control capability employing five vision sensors: two downward-looking cameras positioned on the underneath of the fuselage to enable lateral hover control, two forward-looking in the front for obstacle detection and avoidance, and a 4K imaging camera stabilized by a 3-axis mechanical gimbal. The unit is also equipped with two downward-facing ultrasonic sensors to measure and maintain aircraft height above the ground surface. Its maximum dimension is about 15 inches (as measured across the front of the drone from prop tip to prop tip), it weighs 1.6 pounds, and it employs 8.5-inch propellers.

A series of preliminary test flights were conducted with the Mavic Pro in open air and at the UMWACC facility to become both familiar and comfortable with its flight characteristics and control features. In the dark mine simulator, the absence of light did not allow its optically-based hovering control function to perform. Illumination by mini flashlights temporarily affixed to the wings and underbody of the drone was not sufficient for the drone to establish and maintain its position. Furthermore, the location of some of the flashlights may have interfered with performance of the downward-facing ultrasonic sensors used for height control. During flight tests in the mine simulator, the Mavic Pro became unstable and was nearly impossible to fly in this dark environment.

Figure 28: DJI Mavic Pro

To address the need for better on-board illumination, 24 high-intensity forward-looking LEDs were affixed to the front motor struts and fuselage above the 4K camera (see Figure 29).

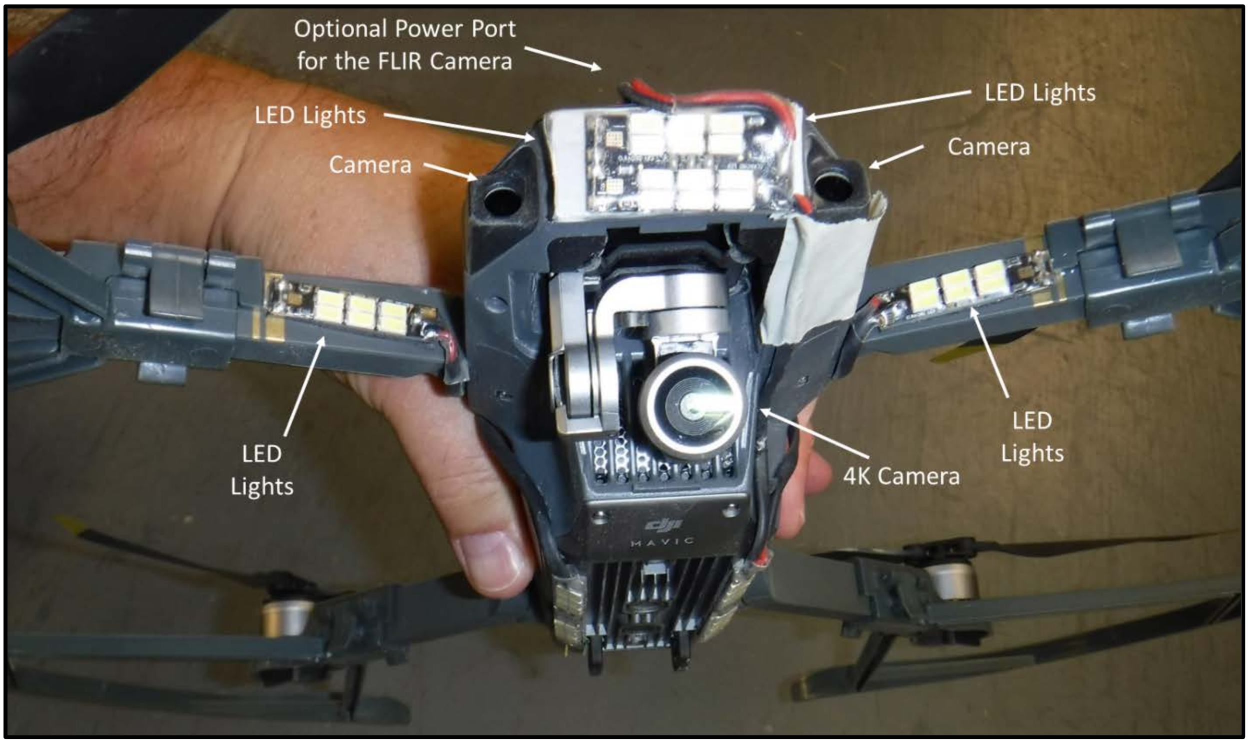


Figure 29: Front view of the DJI Mavic Pro showing added LEDs

Twenty-four (24) high-intensity downward-looking LED lights were also attached to the bottom of the Mavic Pro fuselage as shown in Figure 30. The concept was to attach unobtrusive lighting to enable the drone to establish its position and achieve stable flight in the dark mine opening. In addition, a power port was added to the top portion of the drone to enable future use of a FLIR thermal camera should it be attached to the top portion of the fuselage.

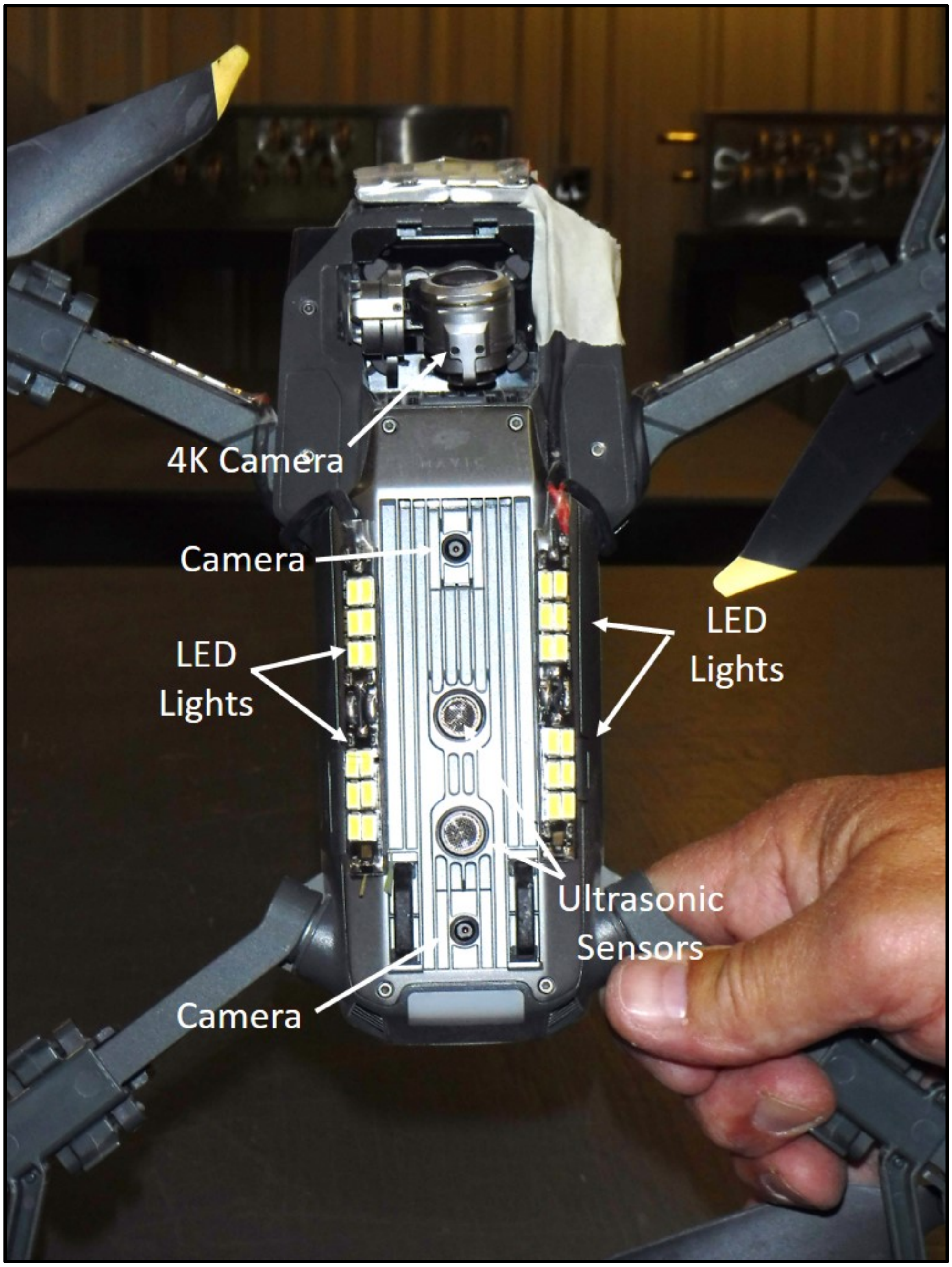


Figure 30: Bottom view of the Mavic Pro showing cameras, sensors, and added LEDs

Following these modifications, additional flight tests were executed in mid-September 2018 in the UMWACC simulated mine. The three flight paths indicated in Figure 31 were selected to evaluate the modified drone's performance.

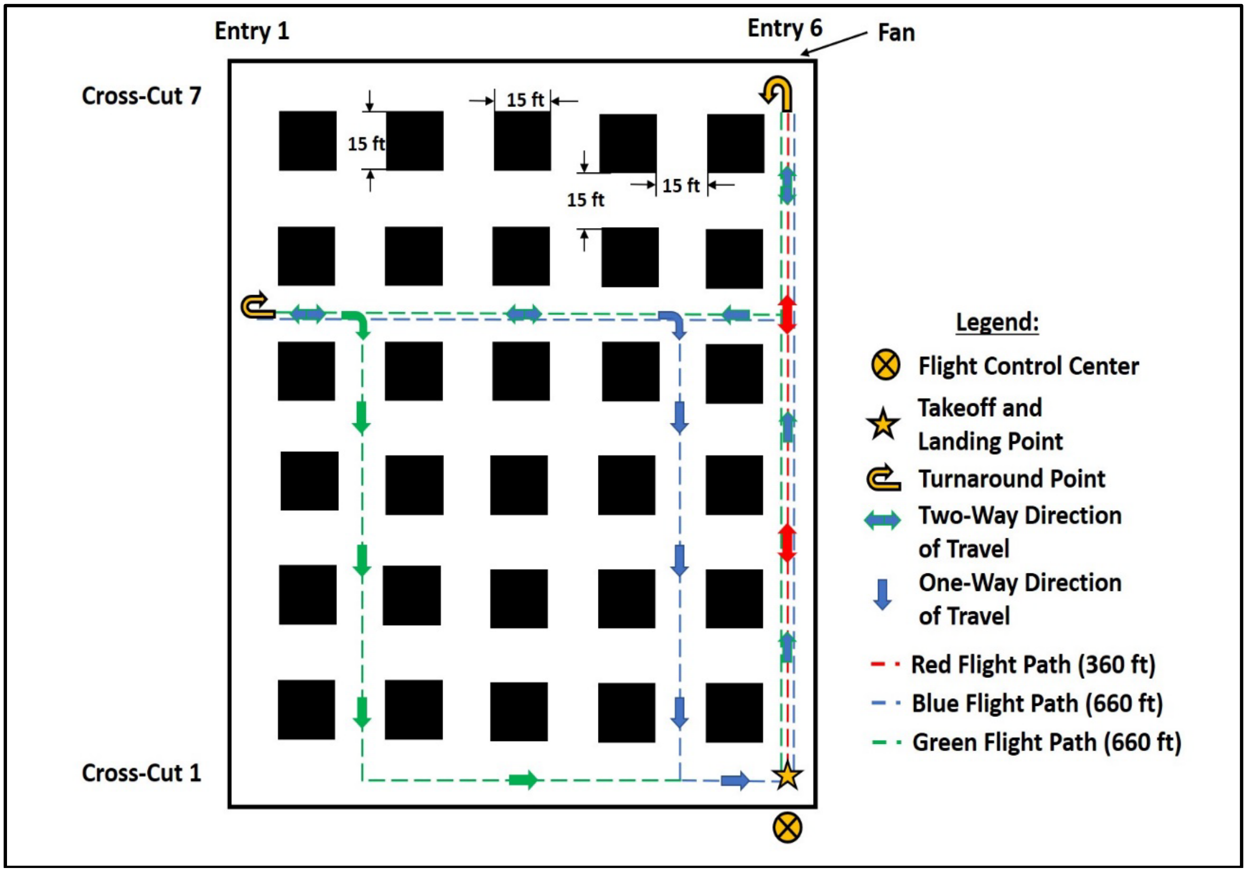


Figure 31: Mavic Pro flight paths in UMWACC simulated mine

The first path, designated as the Red path, was a straight, out-and-back, total 360-foot flight along the No. 6 Entry of the simulated mine.

The second path, designated the Blue path, followed the No. 6 Entry similar to the Red flight path. However, on the return leg of the flight, the drone was turned left into the No. 5 Crosscut, flown the entire length of the crosscut and then was turned around to fly back along the No. 5 Crosscut. The drone was then turned to the right to fly along the No. 5 Entry. Once the drone passed into the No. 1 Cross-cut, it was turned left and flew along the crosscut to the takeoff point. The total length of this flight path was 660 feet.

The final flight path was designated the Green path. This flight path followed the same route as the Blue path except on the return path through the No. 5 Crosscut, the drone was turned left into the No 2 entry. The drone was flown through the entry to the No. 1 Crosscut. The drone was then turned left and flew along the crosscut to the takeoff point. The total length of this flight path was also 660 feet.

During each flight, piloting of the drone was accomplished from a remote location outside of the simulated mine. This arrangement simulated flying the drone remotely from a FAB during a mine emergency. A cellular phone was used to capture the video transmission from the drone. A large monitor was then used to view the video feed instead of FPV goggles. This layout enabled the use of a navigator with the pilot. The navigator was able to monitor and track the overall position of the drone within the mine entry and see obstacles at a distance while the pilot flew the drone (Figure 32).

Figure 32: Piloting the drone at the UMWACC simulated mine

Overall, the modified Mavic Pro performed well. Despite the fact that dust on the mine floor was suspended in the mine opening by the turbulence created by the spinning props, the pilot was able to successfully fly through the simulated mine entries (Figure 33). A maximum controllable flight distance from the pilot's position was not determined as the Mavic Pro was flown across the greatest open extent of the simulated mine. It was determined that both a pilot and navigator are essential to having a successful flight. While the pilot is occupied controlling the drone, the navigator may note and record aircraft progress through the mine structure and identify obstacles, ends of the mine entries, and cross-cuts.

Figure 33: Screen capture from video of the Mavic Pro flying in the simulated mine

5.3.3 Century III Mall Flight Tests

During the week of October 22, 2018, (after the formal conclusion of the technical period of performance), a request was submitted to NIOSH to fly the commercial drones inside the NIOSH Experimental Mine. This location would have been ideal because it is an underground mine, provides a GPS-denied environment, and would pose a more realistic challenge to both the pilot and the drone technology. However, NIOSH constraints for mine access made it impossible to acquire approval in time to meet the project schedule. Permission was then requested to fly the drones at the Century III Mall located in West Mifflin, PA. The mall was selected for the flight tests because it is a large confined space, has two turns in the corridors that would preclude straight line-of-sight flying, and the mall's lowest level provides a mostly GPS-denied environment. On October 26, 2018, permission was granted for flight tests on October 29, 2018

A 1,000-foot flight path was established taking advantage of the longest accessible corridors on the lower level of the mall (Figure 34). The drones could possibly fly in an easterly straight-line direction for about 750 feet from a takeoff point and then turn northeast about 30° and continue for about 125 feet. The path then turned another 20° to the north-northeast direction and proceeded for another 125 feet to the terminus landing point. The pilot remained at the takeoff point and flew the drones without the aid of GPS for the entire duration of each flight.

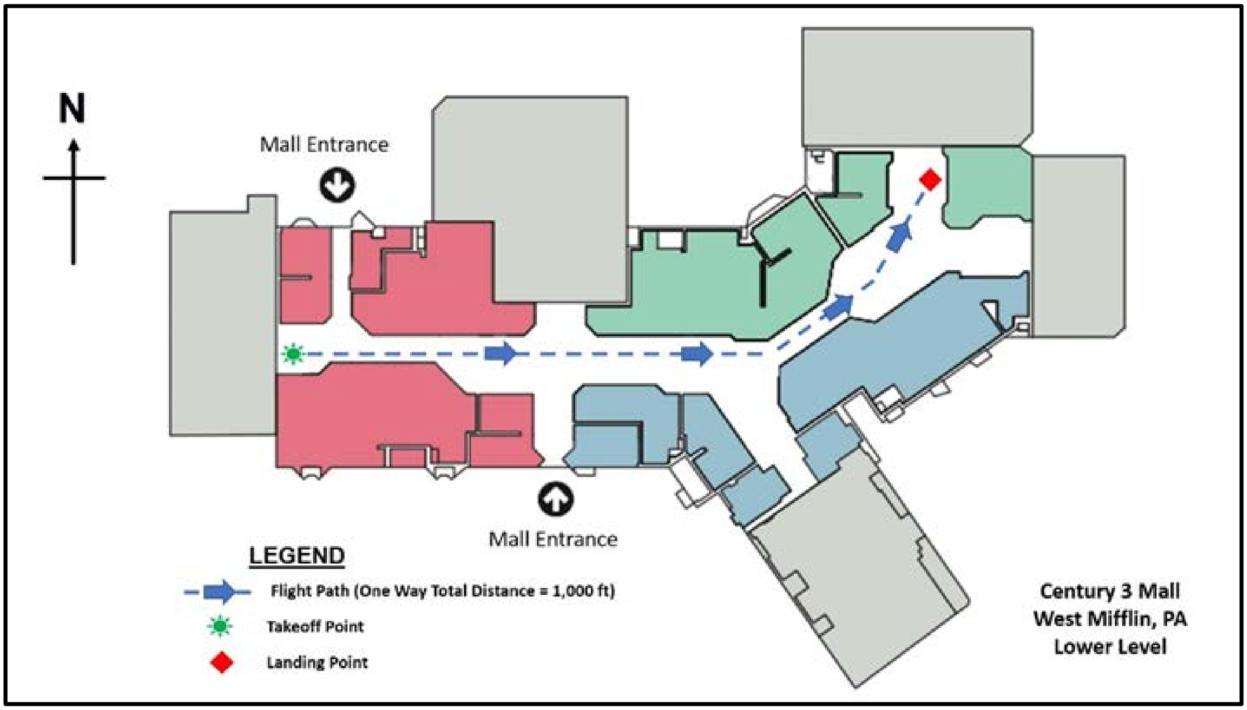


Figure 34: Flight path layout in the Century III Mall, West Mifflin, PA.

In all, three different commercial drones were flown: the DJI Mavic Pro, the Parrot Bebop 2, and the much smaller Parrot Mambo (Figure 35).

Figure 35: Commercial drones flown in the Century III Mall (Parrot Mambo – top left, Parrot Bebop 2 – top right, and DJI Mavic Pro – lower middle)

The Mambo drone was flown by direct observation because it was not equipped with an onboard camera. Because of its smaller size, the Mambo became difficult for the pilot to resolve at distances greater than about 250 feet from the takeoff point. The less capable Mambo drone was only capable of flying for about 500 feet along the straight-line portion of the course before it lost contact with the controller.

The pilot was able to follow the flight of the camera-equipped Mavic Pro and Bebop 2 drones using the FPV output of the controller and an iPhone connected to a large format monitor using Apple TV. The Mavic Pro and the Bebop 2 drones both flew the entire distance of the 1000-foot flight path out and back without difficulty and without landing. Thus, Mission Requirement AVP-4 (Operational Range) listed in Table 12 was attained by these two COTS drones. This demonstrates that a purpose-built drone similar to the Mavic Pro or Bebop 2 airframe most likely could fly inside a confined space for similar distances provided the geometry of the space and layout do not attenuate the signal. Underground flight-testing should be conducted in the future to evaluate effective operational range under realistic in-mine conditions.

6.0 Technology Readiness Assessment

The major goal of this proof of concept contract was to engage, define, and begin to address issues associated with the development and use of an AVP to assist in mine rescue operations. The key issues were the ability of the AVP to function both effectively and safely in the challenging, potentially hazardous underground atmosphere that may be present during a mine emergency.

This section (1) identifies operational issues noted during various flight tests, (2) assesses AVP technology status relative to both intrinsic safety and sensor development for underground guidance, and (3) provides an outline of a development program for a prototype AVP.

6.1 Summary Flight Test Performance Observations

The following section organizes related performance observations from all enclosed space flight tests.

Dust activation and visibility:

- The aircrafts were capable of stirring up and circulating substantial amounts of dust, if present, interfering with visible camera images.
- Aircraft take-off position frequently had to be well above the mine floor to minimize creation of a dust cloud.
- Despite the fact that dust was suspended in the mine opening by the turbulence created by the spinning props, the pilot was able to successfully fly through the enclosed space.

Confined space airflow:

- The negative effect of ground effect turbulence on stable aircraft hovering capability is reduced with increasing elevation above the floor.
- Loss of aircraft control may occur if the geometry of the confined space interrupts uniform airflow to all aircraft propellers.

Airframe construction:

- For successful operation, it is vital to adequately and fully protect propellers.
- A streamlined aircraft profile is necessary to avoid becoming caught on obstructions.
- The structure must be highly crash resistant to protect key components and possibly enable mission continuation after an unplanned landing.
- Ideally, the aircraft should land in an upright position after a crash to enable subsequent takeoff and flight, if possible.
- A smaller aircraft may reduce dust activation and minimize both the influence of ground effect turbulence and the potential for loss of flight control due to airflow restriction.

Robust communications:

- Radio frequency interruption or temporary signal loss can quickly lead to a crash.

Aircraft guidance and navigation:

- Discernable, fixed landmarks or reference points are necessary to perceive drone movement.
- Low-profile reflectors hung from the mine roof greatly facilitated navigation (Note: It would be expected to find similar reflectors and/or reflective signs in an underground coal mine).
- Use of a properly mounted infrared camera or a low-lux visible wavelength camera and an associated built-in light source is critical for successful in-mine flight.
- Flying around corners and in other situations where the pilot does not have a direct line of sight is challenging.
- Introduction of effective auto hover, height control, and collision avoidance systems did mitigate some demands of remote piloting and allowed the pilot to concentrate on maneuvering the aircraft in its immediate airspace.
- Employing both a pilot and a navigator simultaneously observing the same video feed is essential for successful flight operation.
- While the pilot concentrated on controlling the aircraft, the navigator monitored and tracked the position of the aircraft within the mine and detected obstacles at a distance.

6.2 AVP Technology Readiness Assessment

Table 15 is a recap of the requirements list of Table 12 developed with DroneWorks to evaluate the proof-of concept AVP design. The substituted right-hand “Status” column indicates if and how the requirements were addressed.

As explained in Section 4.3, the purpose-designed AVP was not able to be fully flight tested due to motor performance instability. Therefore, the requirements could not be effectively evaluated with that airframe. The “Status” column in Table 15 indicates if the requirements were addressed either through the AVP design and its preliminary testing or in formal flight tests conducted with its surrogate TBS Discovery airframe equipped with the sensors originally installed on the AVP. While key requirements related to aircraft operational control were demonstrated, those related to payload, flight endurance, and hazardous area operation were not.

The custom-designed AVP should have attained requirements AVP-3, -5, and -7 through execution of its engineered design. Flights in excess of 20 minutes were reported by DroneWorks during preliminary, informal AVP flight tests. Also, its rugged central carbon fiber tube skeleton surrounded by a lightweight, flexible shroud completely enclosing the quadcopter’s propellers was intended to maintain airframe and propeller integrity if a crash were to occur.

As outlined in Section 5.2, the most challenging requirement for the AVP concept is that related to its operation in hazardous environments. Given the stated payload and flight duration requirements for the proof of concept AVP derived from the SME feedback (Table 15), the airframe lift necessary to address those requirements resulted in use of electrical power components with voltages and currents substantially exceeding those deemed by MSHA to be inherently safe. While methods may exist to encapsulate those components to isolate them from explosive atmospheres, MSHA requirements to approve encapsulation methods are very stringent. A means to effectively implement these methods needs to be further investigated and pursued more thoroughly prior to proceeding toward prototype development.

Table 15: Demonstration Status of AVP Design Requirements

Requirement Number	Requirement Title	Shall Statement	Verification Method Summary	Status
AVP-1	Manuverability	The aircraft shall be capable of manuevering in all 3 dimensions when operated by a highly trained pilot.	Flight manuverability will be shown during demonstration flights.	Demostrated on 9/9/18 by TBS Discovery
AVP-2	Maximum Dimension	The airframe shall not exceed 30 inches in any dimension when in flight configuration.	The airframe will be inspected and measured to ensure that no dimension exceeds 30 inches.	AVP: 24.7" TBS Discovery: 32"
AVP-3	Useful Payload	The aircraft shall have a payload capacity between 500 and 1000 grams.	The aircraft will be flown with a payload of 1000 grams.	TBS Discovery payload: 982 grams
AVP-4	Operational Range	The aircraft shall be able to maintain positive control link for at least 1000 feet when flown within visual line of sight.	The aircraft will be flown to a distance of 1000 feet.	TBS Discovery 9/8/18 flight test: 1120 feet
AVP-5	Flight Duration	The aircraft shall be capable of maintaing a hover between 20 and 30 minutes.	The aircraft will be hovered in place with a payload of 1000 grams.	TBS Discovery: 13.8 minutes with a 982 gram payload on 9/9/18
AVP-6	Rotor Enclosure	The aircraft shall have a protective enclosure around the rotors.	The airframe will be inspected to verify that the rotors have a protective enclosure.	Inherent in AVP design; limited on the TBS Discovery
AVP-7	Crash Resistance	The aircraft shall be of rugged construction with an emergency landing/collision/crash-tolerant physical configuration.	The aircraft shall be subjected to an unpowered drop from a height of 6 feet (TBR) to a concrete floor without (1) suffering any structural damage to its primary airframe and (2) exposing any of its electronic components (including batteries and motors) either to damage or the ambient atmosphere, if originally isolated from that atmosphere.	Demostrated by 7-foot TBS Discovery crash on 9/9/18 (AVP design was intended to be more resilient and protective)
AVP-8	Hazardous Area Operation	The aircraft shall be constructed to allow its safe operation in hazardous atmospheres	The aircraft and its material parts list shall be inspected to verify construction either (1) with electronic components that possess an intrinsic safety certification, or (2) in a manner isolating electronic components from contact with any explosive atmosphere, or (3) some combination of (1) and (2).	Components with IS certification not available; most components are low power; some encapsulation possible; motors and batteries are greatest concerns per the 9/19/18 MSHA informal IS review
AVP-9	Obstacle Sensing	The aircraft shall be equipped with sensors that allow it to sense obstacles on all six sides (Front, Back, Left, Right, Top, and Bottom).	The design will include the appropriate sensors for flight-test performance evaluation in an enclosed space	Installed on the AVP; transferred and demostrated on the TBS Discovery on 9/9/18
AVP-10	Centering Flight Mode	The aircraft shall have a flight mode where it attempts to center itself within its environment for operation in an enclosed environment.	The aircraft will be flown in an environment demonstrating the centering capability.	TBS Discovery 9/9/18 flight test

Table 16 provides definitions of nine Technology Readiness Levels (TRLs) originally developed by NASA and adopted by the US Department of Defense (DoD) to assess technology maturity. Based upon the results of the investigations contained in this report, the current level of technology for the mine rescue AVP application is assessed to be at TRL 5, as highlighted in the table.

TRL 5 was identified primarily because the motors and batteries planned for use on the custom-designed AVP airframe are not be capable of achieving MSHA intrinsic safety approval in their current state. If the ability of the AVP to function effectively in an underground coal mining environment were the only consideration in assessing technical readiness, the development of the purpose-built airframe, successful demonstration of guidance sensor technology (infrared ranging, infrared and low-lux cameras), and identification of specific operational issues encountered in simulated mine settings would support a TRL-6 rating.

Table 16: Department of Defense (DoD) Technology Readiness Level (TRL) Definitions

Level	Definition	DoD DAG Description
1	Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples might include paper studies of a technology's basic properties.
2	Technology concept and/or application formulated.	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.
3	Analytical and experimental critical function and/or characteristic proof of concept.	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4	Component and/or breadboard validation in laboratory environment.	Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared to the eventual system. Examples include integration of "ad hoc" hardware in the laboratory.
5	Component and/or breadboard validation in relevant environment.	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment.
6	System/subsystem model or prototype demonstration in a relevant environment.	Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness.
7	System prototype demonstration in an operational environment.	Prototype near, or at, planned operational system. Represents a major step up from TRL 6, requiring demonstration of an actual system prototype in an operational environment such as an aircraft, vehicle, or space.
8	Actual system completed and qualified through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.
9	Actual system proven through successful mission operations.	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. Examples include using the system under operational mission conditions.

6.3 Outline for a Prototype AVP System Development Program

Significant technical advancements made during this grant include:

- Validation of capabilities necessary to support the mine rescue mission
- Implementation of design attributes to support the mine rescue mission
- Demonstration of sensor technology necessary to effectively guide an AVP through an unilluminated confined space
- Demonstration of the ability to operate an AVP over significant distances from a fixed location in both a simulated and an actual coal mine environment
- Development of an understanding of operational issues associated with AVP flight in a coal mine environment
- Identification of the major impediments to achieve AVP certification for use in hazardous atmospheres
- Definition of a path to achieve AVP IS certification and the offer of ongoing, informal support by MSHA A&CC personnel to consult on development of that path

Significant challenges to further advancement of the TRL level of AVP (and a UAR system) development lie in the areas of IS design necessary to permit operation for mine rescue support and robust underground communications to enable reliable longer-range operation. Both of these challenges may be addressed by building upon the advances listed above.

As noted in Section 5.2, to achieve an AVP design capable of MSHA approval for use in hazardous underground environments, the design process should first focus on intrinsic safety requirement considerations. The remaining SME-suggested performance requirements would then be addressed as possible within the IS-imposed constraints. The specific suggestion made by MSHA personnel was that the design process should start at the AVP power supply (battery) and then examine what commercial motors might successfully operate with current and voltages limited by IS requirements.

If SME-derived performance requirements AVP-3 and -5 were relaxed, a smaller airframe employing less powerful motors and batteries could be designed for the AVP application. Adopting this approach would better enable a future AVP design to achieve a safety certification. A smaller airframe design would also assist in alleviating the potentially adverse effects ground effect turbulence and non-uniform airflow discussed in Section 5.2.

In practice, use of a smaller AVP might also necessitate adoption of a CONOP employing multiple AVPs flying one-way reconnaissance missions ahead of mine rescue teams. A major possible benefit of adopting a "one-way mission" CONOP could be that each AVP sent ahead of the mine rescue team could serve as a node in an AVP-specific mesh communication system. That system would then be capable of extending AVP flight control and data transmission over longer distances from the mine rescue fresh air base, well beyond current line-of-sight underground communication capabilities.

Therefore, re-examination of the AVP design based upon the lessons learned from this grant offers the opportunity to attain the ultimate objective of this effort, providing mine rescue and recovery personnel an aerial reconnaissance capability to acquire timely, accurate, and reliable information upon which to base their actions.

7.0 Appendices

7.1 Appendix A: Subject Matter Expert Affiliation

SME Affiliation	Organization Type
Kentucky Training Center	Academia
MSHA	Academia
Alliance Resources	Company
Alpha Natural Resources	Company
Black Hawk Mining	Company
Black Hawk Mining	Company
Black Hawk Mining	Company
Black Hawk Mining	Company
Consol Energy	Company
Contura Energy	Company
United Coal Company	Company
United Coal Company	Company
United Coal Company	Company
United Coal Company	Company
United Coal Company	Company
Independent Consultant	Contractor
MSHA, Approval & Certification Center	Federal Agency
MSHA, Mine Emergency Operations	Federal Agency
MSHA, Mine Emergency Operations	Federal Agency
MSHA, Mine Emergency Operations	Federal Agency
MSHA, Mine Emergency Operations	Federal Agency
MSHA, Mine Emergency Operations	Federal Agency
MSHA, Mine Emergency Operations	Federal Agency
MSHA, Mine Emergency Operations	Federal Agency
MSHA, Mine Emergency Operations	Federal Agency
MSHA, Mine Emergency Operations	Federal Agency
MSHA, Program Evaluation and Information Resources	Federal Agency
NIOSH	Federal Agency
NIOSH	Federal Agency
Unknown	Contractor (?)
Kentucky	State Agency
Ohio	State Agency
Pennsylvania	State Agency
Virginia	State Agency
Virginia	State Agency
West Virginia	State Agency
West Virginia	State Agency
Innovative Wireless Technologies	Vendor

7.2 Appendix B: Online Survey Questions

Attention Mine Rescue Team Expert - We Need Your Help!!

Mine Rescue Team Expert: The Alpha Foundation for the Improvement of Mine Safety and Health recently awarded a Technology Development contract to the United Mine Workers of America Career Centers, Inc. Alpha's Technology Development projects are directed towards building some tangible device, instrument, or machine that addresses a targeted area of mine safety and health. The UMWACC's project is entitled "Intrinsically Safe Underground Aerial Reconnaissance Platform Development". The objective of this contract is to design, assemble, and demonstrate a purpose-built aerial platform capable of safely maneuvering through hazardous underground atmospheres to assist in mine rescue and recovery operations. To meet our objective, we need your expert opinion to define a realistic mission with specific goals for the unmanned platform and to develop a reasonable concept for how this capability might be employed by rescue teams. The attached short survey will help us to capture your ideas and opinions. We realize that your time is valuable and we sincerely thank you for your important input and help! Please complete this survey no later than December 8, 2017.

1. Do you think an Unmanned Aerial Vehicle (UAV) could be a useful tool to rescuers in post-event operations?

Strongly Disagree	Disagree	Neither Disagree or Agree	Agree	Strongly Agree
○	○	○	○	○

2. How could the UAV benefit or assist the rescuers? Check as many that apply.

- ☐ Exploration ahead for hazards (roof falls, debris fields, ponded water, hot spots)
- ☐ Mine atmosphere sampling
- ☐ Locating injured miners
- ☐ Examining refuse alternatives for occupancy
- ☐ No benefit might slow down the team's progress

3. Would you launch a non-permissible UAV if mine rescue teams cannot be deployed because of dangerous post-event conditions?

Strongly Disagree	Disagree	Neither Disagree or Agree	Agree	Strongly Agree
○	○	○	○	○

4. Who should make the decision to launch the UAV?

Official in the Command Center	Mine Rescue Team Member	State Government Official	Federal Government Official (MSHA)	Other
○	○	○	○	○

5. What is the optimal mission flight time?

≤ 15 Minutes	16 to 30 Minutes	31 to 45 Minutes	46 to 60 Minutes	Flight time is dependent on the mission and tasks
○	○	○	○	○

6. What is the optimal flight range for a UAV for underground use?

≤ 250 Feet	251 to 500 Feet	501 to 750 Feet	751 to 1000 Feet	> 1000 Feet
○	○	○	○	○

7. What is the optimal size for a UAV for underground use?

≤ 12 Inches	13 to 18 Inches	19 to 24 Inches	25 to 30 Inches	> 30 Inches
○	○	○	○	○

8. Should the UAV fly back to takeoff point or should it land in the mine after the mission and be recovered later after safe power down?

Always Return to takeoff point	Always land after in the mine after the mission is completed	The decision is up to pilot depending on power and mission
○	○	○

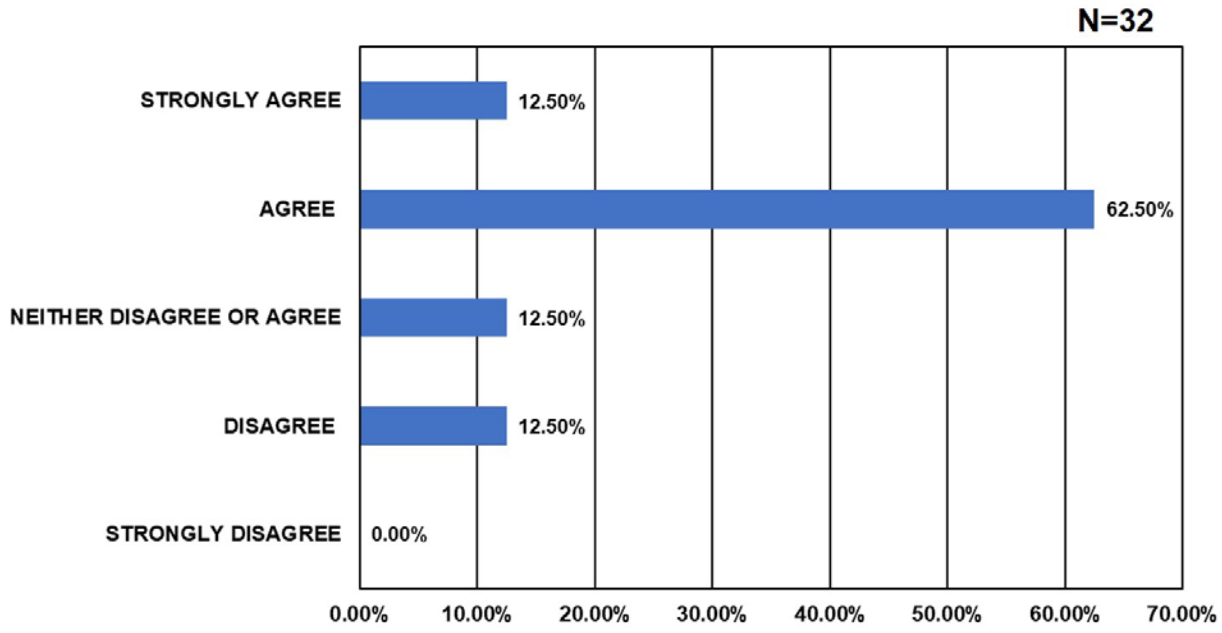
9. Should the UAV have other underground uses in addition to mine rescue team assist?

Strongly Disagree	Disagree	Neither Disagree or Agree	Agree	Strongly Agree
○	○	○	○	○

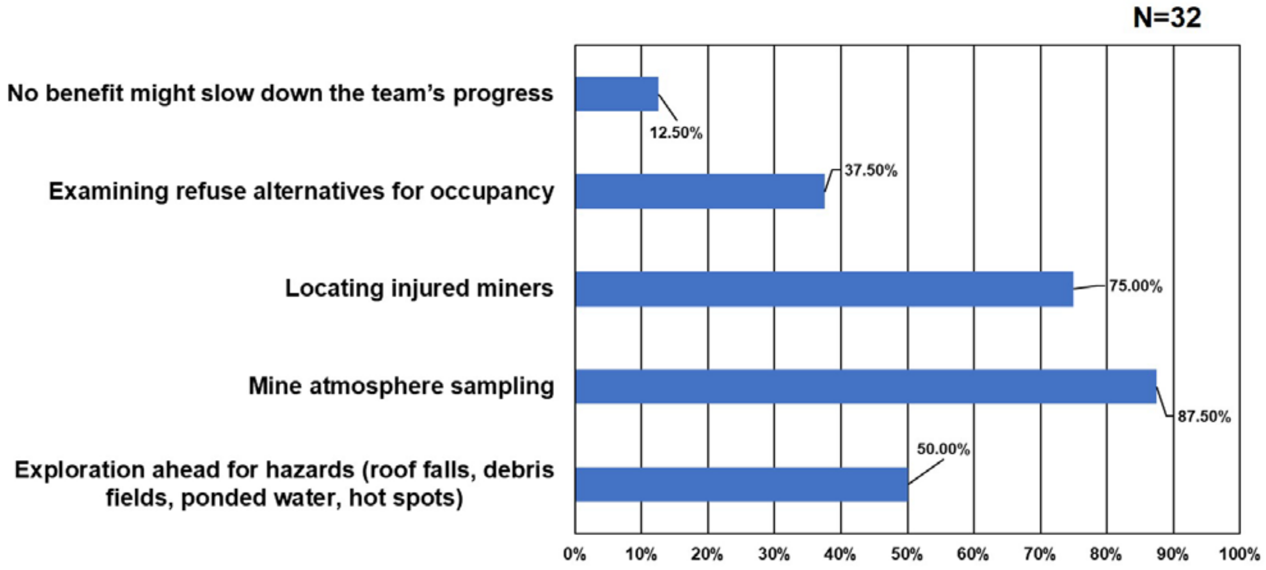
10. Your ideas and opinions are important to us, please share them below.

7.3 Appendix C: Online Survey Results

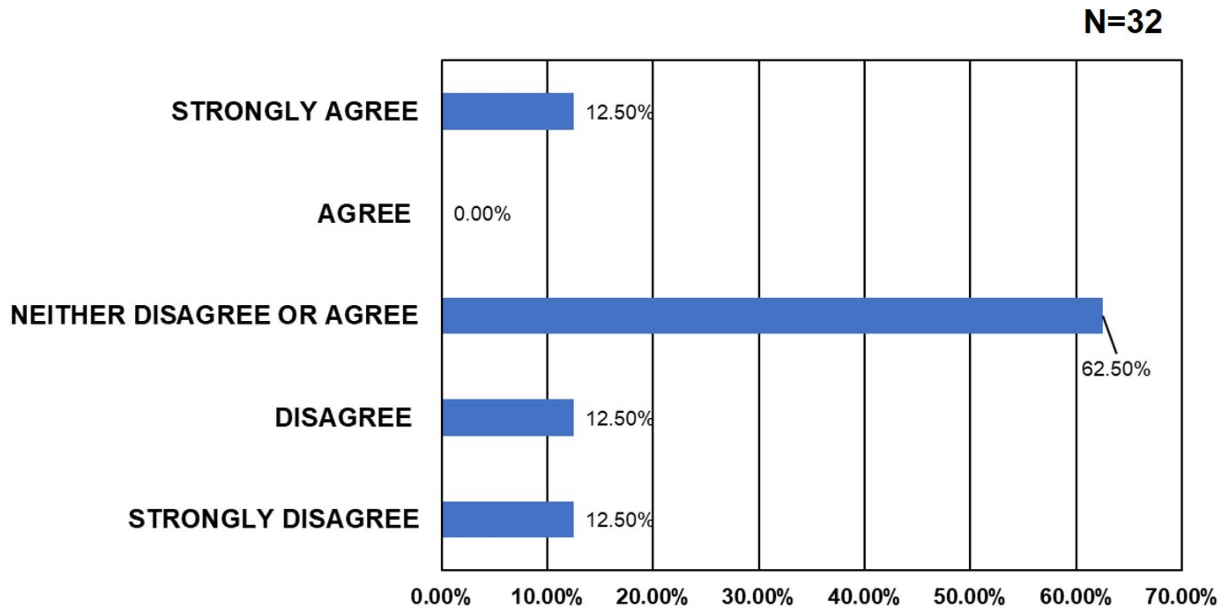
Q1: Do you think an Unmanned Aerial Vehicle (UAV) could be a useful tool to rescuers in post-event operations?



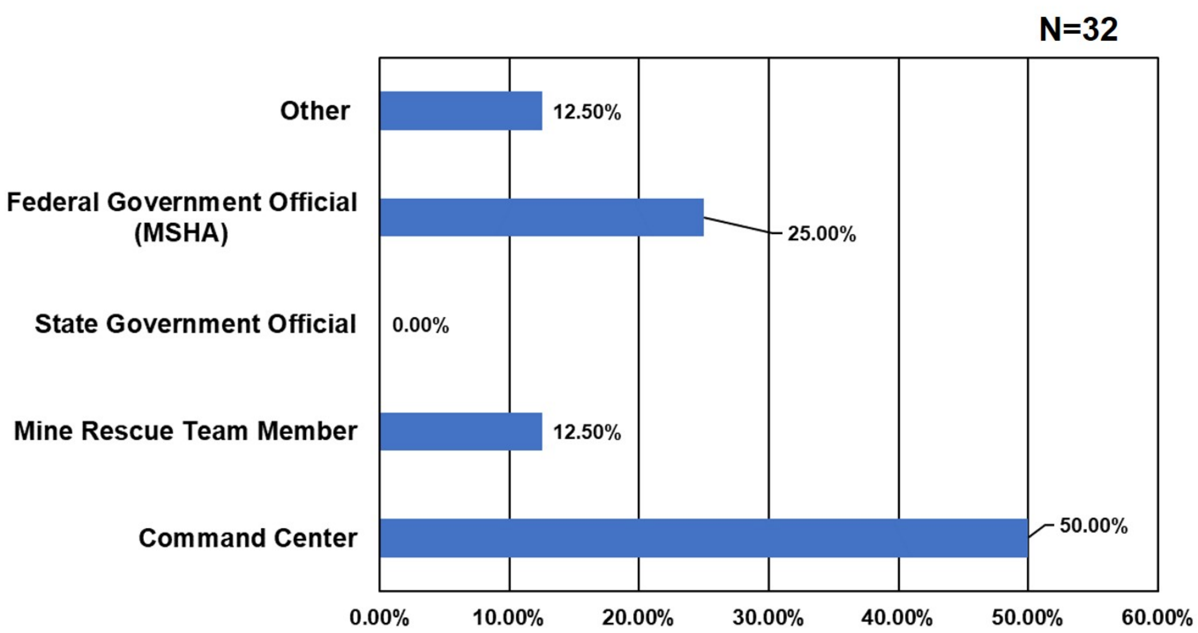
Q2: How could the UAV benefit or assist the rescuers? Check as many that apply.



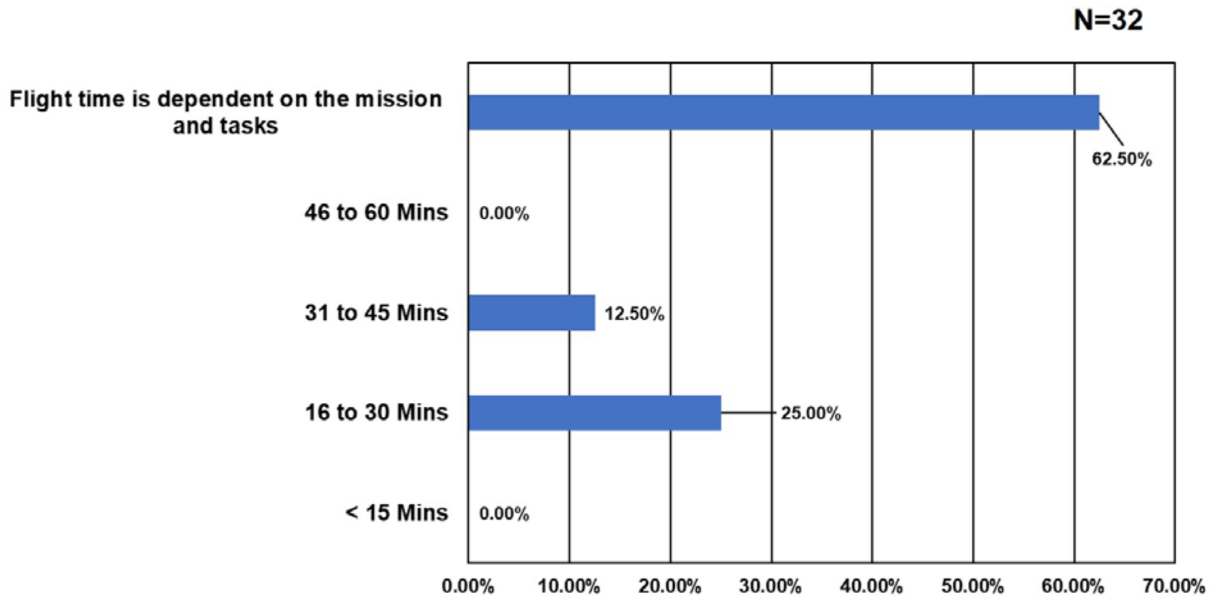
Q3: Would you launch a non-permissible UAV if mine rescue teams cannot be deployed because of dangerous post-event conditions?



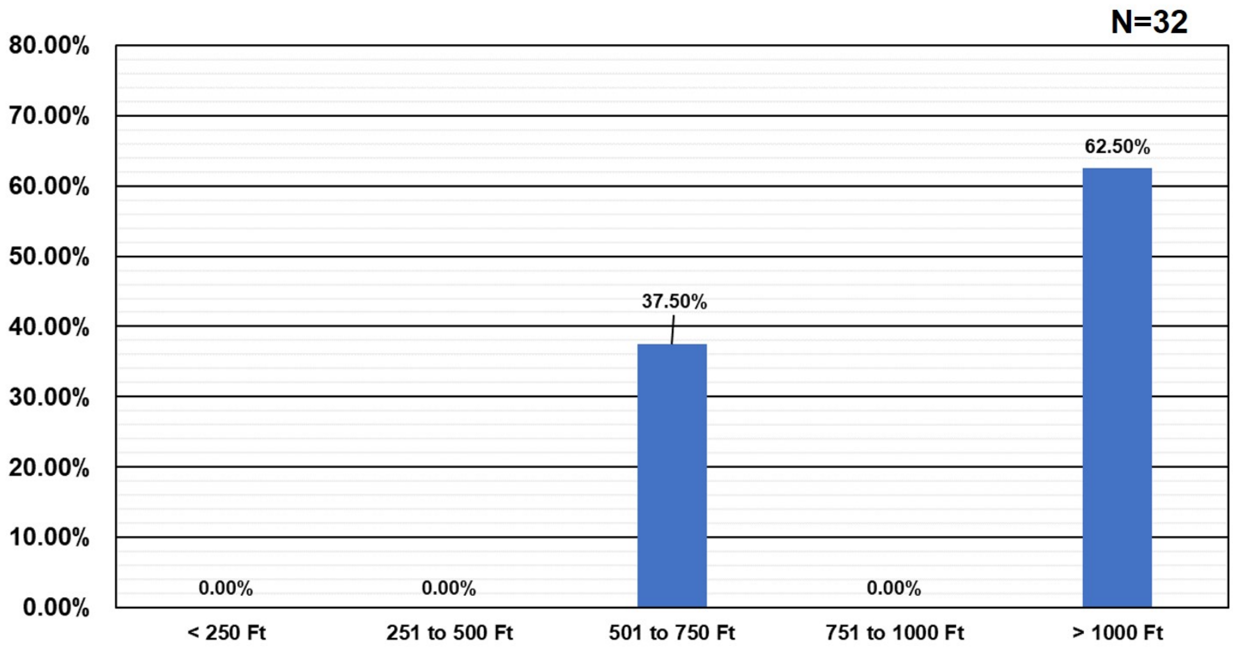
Q4: Who should make the decision to launch the UAV?



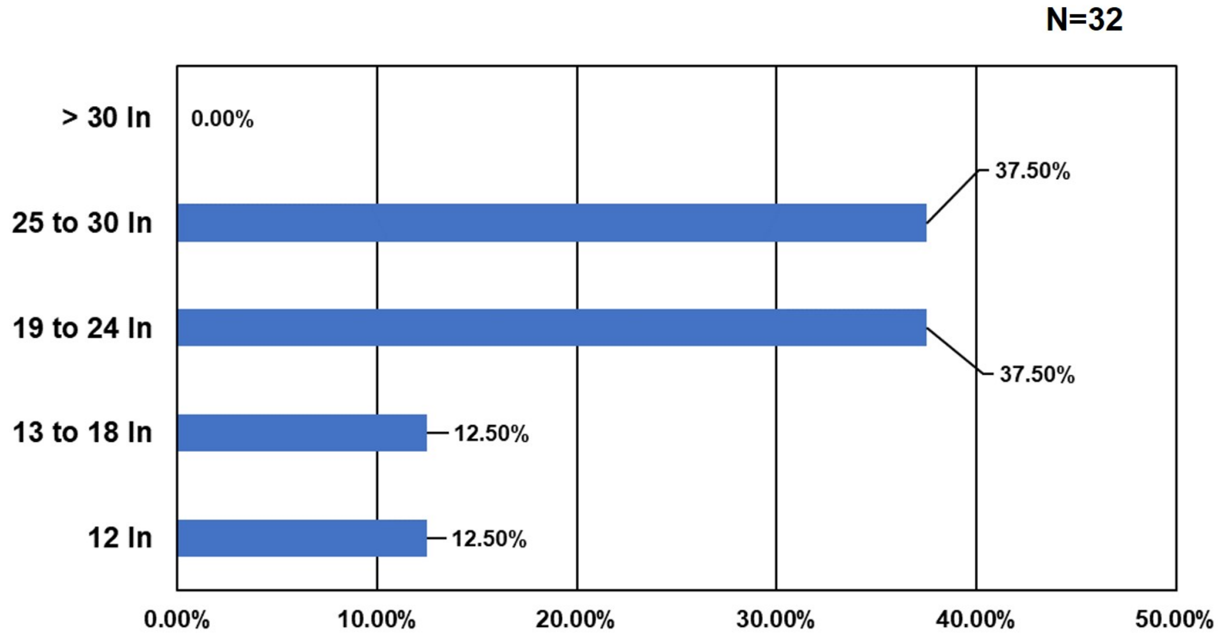
Q5: What is the optimal mission flight time?



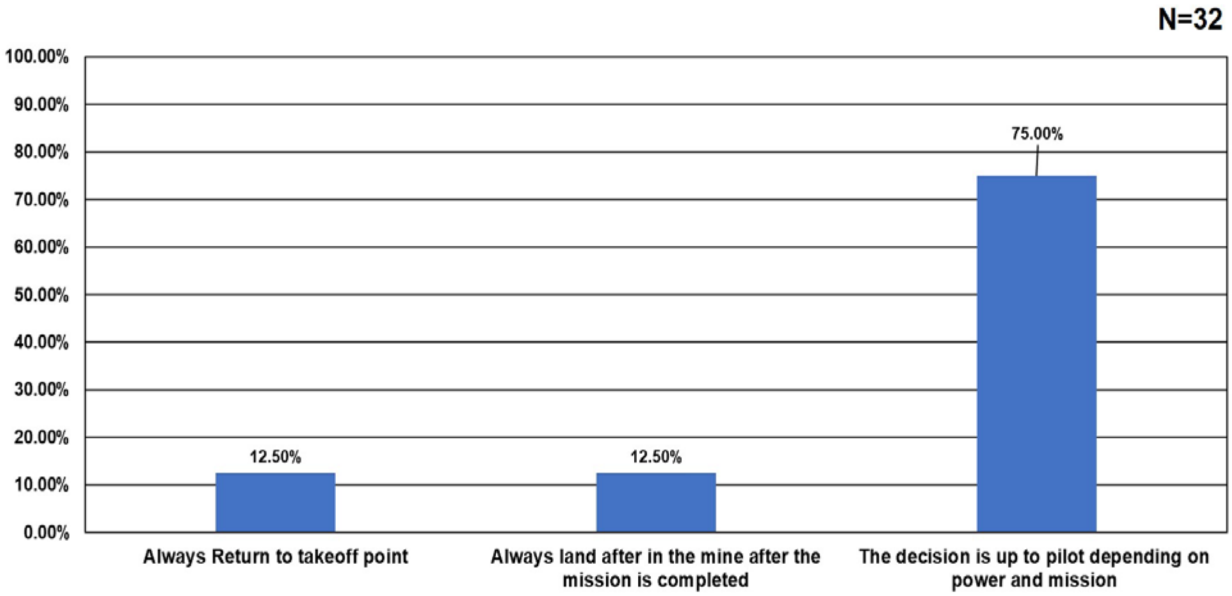
Q6: What is the optimal flight range for a UAV for underground use?



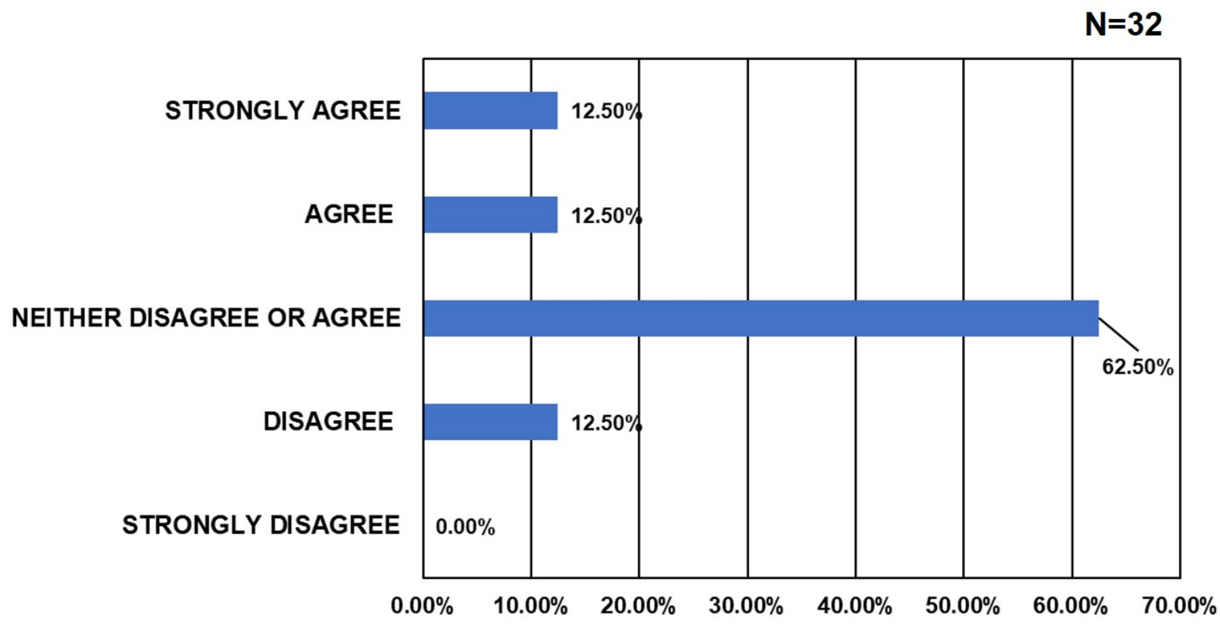
Q7: What is the optimal size for a UAV for underground use?



Q8: Should the UAV fly back to takeoff point or should it land in the mine after the mission and be recovered later after safe power down?



Q9: Should the UAV have other underground uses in addition to mine rescue team assist?



Comment Box: Your ideas and opinions are important to us, please share them below.

N=3

No. 1: I think a permissible (intrinsically safe) UAV may be usefully deployed in advance of mine rescue explorations. Confined space and lack of visibility may be limiting factors. In my experience with remote devices, travel distance and operation are affected by line-of-site. Given the dynamics of underground mining, a UAV would likely be limited to straight in, straight out flight in each entry. Pilots/operators would have to monitor signal strength diligently. That said, I think a UAV equipped with FLIR vision and gas monitoring capabilities may be of some use.

No.2: I was in the Aracoma mine accident and the smoke was too thick to use any type of aircraft, Sago also had too much dust in suspension. Wasting precious time; we need to get to survivors.

No.3: The issue of intrinsically safe or not presents a difficult choice for those making decisions to fly or not-to-fly the UAV. I think that the decision would have to be based on factors like flight path, distance from the fresh air base, potential obstacles and mission purpose (to look for miners or to collect atmospheric information).

7.4 Appendix D: Questions Presented to the Mine Rescue Experts

General Questions

1. Do you think an Unmanned Aerial Vehicle (UAV) could be a useful tool to rescuers in post-event operations?
2. How could the UAV benefit or assist the rescuers? Or would it just slow them down?
3. What possible missions would you use the UAV for? Could a UAV be used in place of a rescue team?
4. Step by Step, what are your initial thoughts on how the UAV might operate? What specifically would you want the UAV to accomplish?
5. What information would want the UAV to gather?
6. How should the UAV gather this information, i.e. live feed? Still images?
7. How should the information gathered by the UAV be shared? Should it be reviewed before sharing? Who should have access to the information? Who should interpret the information gathered by the UAV?
8. Who should own/operate/maintain the UAV?
9. Does the UAV have to be intrinsically safe/permissible?
10. Are there any possible missions for a UAV that is not intrinsically safe/permissible?
11. How many people should participate in the UAV mission? Should everybody have the same UAV system? Who should make the decision to launch the UAV?

Specific Operational Questions

1. Who should operate the UAV? Should a UAV operator train in unison with a rescue team?
2. If payload becomes an issue, does that affect its suitability or usability?
3. If payload becomes an issue, can you prioritize the capabilities of the UAV? i.e. live feed vs camera; gas readings such as just methane vs carbon monoxide, oxygen, and methane?
4. Should batteries be able to be changed out underground? How long should the UAV be able to operate for a mission? What if that time was reduced to 20-30 minutes? How does this affect your perception of the UAV's usability?
5. What other power system should be considered?
6. What type of controller should it have?
7. What type of propulsion system should a UAV have?
8. What is the optimal size for a UAV for underground use?
9. What type of guidance system is optimal for a UAV?
10. What should the range of a UAV be?
11. How maneuverable should the UAV be?
12. Should there be a battery indicator?

8.0 Acknowledgement/Disclaimer

This study was sponsored by the Alpha Foundation for the Improvement of Mine Safety and Health, Inc. (ALPHA FOUNDATION). The views, opinions and recommendations expressed herein are solely those of the authors and do not imply any endorsement by the ALPHA FOUNDATION, its Directors and staff.