UAVs for Wilderness Search and Rescue: Real-World Considerations and Technology Roadmap for Fixed Wing UAVs

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Abstract

Wilderness search and rescue is predominantly conducted by ground based teams, however its limitations have encouraged the use of alternative approaches. Aerial search and rescue provides complementary capabilities as it has a higher areal coverage rate and can survey challenging terrain that is not easily accessible. Helicopters and other manned aerial vehicles dominate aerial search, but disadvantages, such as the need for highly trained personnel, slow response time, and high capital requirements, limit their use.

Unmanned aerial vehicles (UAVs) capture the benefits of helicopters while overcoming many of the associated drawbacks that limit their use for wilderness search and rescue. Here we demonstrate the need for UAVs in wilderness search and rescue. We compare the two main types of UAVs—fixed wing and rotary—along three performance factors, including flight range, image quality, and degree of control over the flight path. Theoretical and practical considerations for fixed wing UAVs are explored. Finally, we present practical technology ideas to improve the utility of both fixed wing and rotary UAVs.

This work offers an introduction to aerial search and rescue with UAVs, assesses real-world tradeoffs between fixed wing and rotary UAVs, and presents a roadmap for further technology development to advance this technology into the field.

KEYWORDS: *UAVs, fixed wing UAVs, rotary UAVs, wilderness search and rescue, aerial search and rescue*

Introduction

Aerial search and rescue complements existing efforts

The search for lost persons in wilderness settings is primarily conducted on foot as it is readily available, low cost, and requires minimal training (Heggie & Heggie, 2009). Ground search and rescue (gSAR) is well suited for thorough exploration of a few areas. However, it is suboptimal in situations where the search area is large or when the terrain is challenging (e.g. mountainous regions, heavily forested area, rocky coastlines, etc.). In these cases, aerial search and rescue (aSAR) can be used to augment ground based efforts (Tomazin & Kovacs, 2003). Traditionally, aSAR is performed with helicopters and, occasionally, other manned aerial vehicles (e.g. gliders, small propeller planes, etc.).

UAVs can perform aerial search when helicopters are unavailable

Helicopters allow search and rescue teams to quickly search a large area and carry equipment for the rescue. However, helicopters have many limitations that restrict their use. Helicopters require multiple highly trained personnel—a pilot, spotters, hoist operator, and rescue specialist—to operate effectively, creating the need to have multiple trained personnel on staff and available during an emergency ("Priority 1 Air Rescue"). Additionally, the initial capital investment required to buy a helicopter is significant, as demonstrated by the Canadian government spending $20 million to maintain their fleet ("Federal Search and Rescue Activities," 2013). Even when a helicopter is available, it is expensive to operate. The United States National Park Service spends a large fraction of its search and rescue budget on aircraft (Heggie & Amundson, 2009). Together, the high cost and significant training requirements limit the use of helicopters to a subset of search and rescue missions.

Given the effectiveness of aerial search and rescue, it is natural to explore additional technologies to supplement helicopters. Unmanned aerial vehicles (UAVs) can cover large, and potentially challenging, areas quickly while requiring significantly reduced training and capital investment.

Fixed wing UAVs vs Rotary UAVs

Introduction to fixed wing & rotary UAVs

UAVs can be classified into two main categories, fixed wing or rotary, based on how each generates lift. Each UAVs differs in its flight dynamics and hardware specifications which affects flight range, image quality, and degree of control over the flight path.

Fixed wing UAVs (fwUAVs) consist of an airfoil with one or more propellers mounted horizontally. In order to create lift, fwUAVs rely on actuated elevators and/or ailerons which control pitch, yaw, and roll simultaneously. As the airfoil moves through the air, it generates lift. This lift is enough to overcome the drag force and thus allows fwUAVs to glide (Nakamura, 1999). In general, fwUAVs must maintain forward velocity relative to the surrounding air to maintain altitude, which precludes hovering in the traditional sense.

The propellers on rotary UAVs (rUAVs) are oriented vertically. Forward motion is generated by adjusting the speed of the propellers to tilt the entire rUAV. This change in pitch allows the propellers to both keep the rUAV airborne and propel it in the direction of the tilt. This enables both hovering and precise motion in any direction. Due to their ease of use and low cost, rUAVs have gained popularity recently, especially within the consumer electronics sector.

Differences in performance between fixed wing and rotary UAVs

Fundamental differences between how fixed wing and rotary UAVs fly affect the capabilities and, ultimately, the optimal use cases for each type of UAV. fwUAVs are designed to have a high glide ratio. Therefore, they consume significantly less power than rUAVs. This allows fwUAVs to fly longer distances and remain airborne for longer periods of time compared to similarly sized rUAVs. The ability to perform longer missions enables larger areas to be searched more quickly and with less frequent interruptions.

Gliding confers additional advantages to fwUAVs: the ability to carry increased payloads during flight. Larger payloads allow the UAV to carry a larger battery to extend flight range or a higher quality imaging system (e.g. camera, lens, stabilization, remote data transmission). Improvements in image quality in the form of increased resolution, decreased noise, more effective image stabilization and decreased lens aberrations can enable better localization of targets. Many of these factors are coupled. For example, as image quality improves, the UAV can fly at a higher altitude increasing the field of view enabling an area to be searched more quickly without compromising probability of detection when other factors are held constant.

In contrast, rUAVs, which generate lift via vertically oriented propellers, can maintain a fixed position by hovering in place. This allows them to more thoroughly explore an area of interest. This enables the UAV to perform well in a hasty search where a few highly relevant locations are searched initially (Kentucky Emergency Management, 2014). The precise control that rUAVs offer enables intuitive real-time operator control. The ability to change direction and maintain lift without maintaining forward velocity provides the necessary flexibility to follow almost any flight path.

Given their improved range and imaging systems, fwUAVs provide the most benefit where ground search and rescue fall short: in searching large areas and challenging terrain. The most significant advantage of rUAVs, the ability to hover and, therefore, thoroughly explore an area of interest, augments the existing capabilities of ground search and rescue. Therefore, fwUAVs should be better suited to complement traditional gSAR. This will likely manifest by performing thorough grid searches of an area, often in regions not easily accessible to a ground team (Kentucky Emergency Management, 2014). **Figure 1** illustrates this and other trade-offs between fwUAVs and rUAVs.

	Fixed wing UAVs	**Rotary UAVs**
Illustration		
Propulsion system	Lift generated through forward motion	Lift generated independently of motion
Flight range	Longer flight distance and duration	Shorter flight distance and duration
Payload	Higher	Lower
Image quality	Higher	Lower
Hovering	Unable to hover as it must maintain forward motion to remain airborne	Capable of hovering and flying in any direction
Ease of use	Assembly and training required	Straightforward
Cost	Higher priced	Lower priced
Preferred use case	Grid search	Hasty search

Figure 1. Fixed wing UAVs versus rotary UAVs. *A comparison of the relative performance of fixed wing and rotary UAVs in a general case of an approximately fixed budget. Exceptions can be found at very high or low budgets where other design compromises have been made.*(DJI, 2018; Rees, 2016)

Real-world shortcomings with fixed wing UAVs in the field

Beyond considering the theoretical differences between fixed wing and rotary UAVs, practical considerations must be examined as they can play a significant role in establishing the effectiveness of UAVs for SAR. Prior work has examined real-world experiences with rUAVs (Goodrich, Morse, Engh, Cooper, & Adams, 2009). The recent emergence of fwUAVs demands an evaluation of the unique challenges and opportunities they may pose. Due to the large commercial interest in rotary UAVs, their technology is significantly more mature which results in a more robust platform. This is critical for search and rescue applications where technology must be resilient to faults, offer an intuitive user interface, and, most importantly, perform consistently under challenging operating conditions. The differences between fwUAVs and rUAVs are especially apparent for ruggedness, launch and landing, image quality, and real-time control. For a summary, see **Table 1**.

Table 1. Practical shortcomings of fixed wing UAVs. *Our experience with a fixed wing UAV indicated that commercially available fixed wing UAVs currently fail to meet the demanding applications of wilderness SAR. Improvements in hardware and software are needed to improve their suitability for SAR.*

Portability, assembly, ruggedness	• Wingspan > 1 meter was difficult to transport • 15 to 30 minutes of assembly and set-up required prior to launch • Susceptibility to temperature, humidity, and wind
Launch & Landing	• Requires unobstructed 30 x 30 meter area for safe landing • Launch: assisted success rate of 40-90% depending on payload and weather conditions • Landing: vegetation, gravel, sand damaged UAV
Image quality	• Vibrations from motors introduce motion blur into images • Lack of camera stabilization adversely affected our ability to interpret images
Real time control	• Real-time human-in-the-loop control is difficult as forward motion is required during flight

Assembly and ruggedness

If UAVs are to play a critical role in SAR missions, they must operate reliably even in adverse conditions such as rocky, muddy, or sandy terrain, high winds, and demanding time constraints. They must integrate into the workflow of rescuers by allowing for simple transportation, set-up, and operation.

The major benefit of fwUAVs—the large airfoil that enables gliding—also poses a challenge when considering portability. Further, oftentimes fwUAVs need to be assembled at the launch site prior to beginning a mission. This adds both complexity and time to the beginning of the search which ultimately affects the ability to locate and rescue a missing subject.

These challenges are further exacerbated by the nascent state of fwUAV hardware. Many solutions require the end user to integrate separate hardware components, such as radios, cameras, and flight control systems. Not only does this increase the risk of system failure, but dramatically affects its ruggedness. The ability to operate reliably in a harsh environment with unstable temperatures, humidity, and weather conditions as well as withstand contact with sand, gravel, and/or vegetation upon landing is critical to the successful deployment of UAVs for SAR.

Launch and landing

Launching fwUAVs can be a risky process that requires both operator skill and environmental conditions to be favorable. The types of launch styles for fwUAVs can be classified into two main classes: self-propelled and assisted launch. Self-propelled launches rely solely upon the power of the UAV to gain enough momentum to achieve lift and become airborne. This is analogous to conventional airplanes, which use a runway to gain speed. As an alternative, assisted launches rely upon an external force, such as a human operator or a catapult, to provide the initial momentum. These UAVs can be substantially smaller, lighter, and more energy efficient than those that must independently propel themselves during launch. As such, assisted launch UAVs are currently much better suited for SAR than those that utilize a self-propelled launch. The most portable and versatile of the assisted launch UAVs forgo the catapult for a human powered launch. Unfortunately, this introduces risk as an imprecise throw by a human operator can compromise the launch of the UAV. Despite the risk, these UAVs are becoming more widespread as portability becomes more critical and advances in flight control techniques can more readily compensate for the variability in human assisted launches.

Similar to an airplane, fwUAVs traditionally require large areas of unobstructed, level ground into which to land themselves. Coupled with the inherent uncertainty of inertial navigational systems and potentially adverse weather conditions (e.g. wind), this need can place limitations on where a team can base an aSAR mission. Other technologies enabling landings in small or obstructed areas include the use of large nets or arresting hooks (Fundacion EcoMinga, 2016; Lockheed Martin, 2005)

In contrast, because rUAVs are capable of vertical flight, the constraints on where a rUAV can launch and land are much less stringent. However both fwUAVs and rUAVs rely on GPS and magnetic compass signals for orientation and navigation. The GPS signal can be compromised due to obstructions or reflections of the signal. The presence of large metal structures can introduce an error into the compass. Most UAVs rely on radio communications to stream information, including video data, to the operator in real-time. Being located proximal to the UAV ensures high fidelity radio communications. All of these considerations further restrict potential base areas for both UAV types.

Without systematically addressing these issues, a SAR team could compromise the effectiveness of a search by selecting either a very safe site, which places the team far from the search area, or one that is too obstructed, which risks the safety of the UAV and may preclude the aSAR team from getting the UAV off the ground or back safely.

Image quality

The difference in maturity between fwUAVs and rUAVs affects image quality. Propellers and turbulent wind induce high frequency vibrations throughout the body of the UAV. Passive vibration rejection systems—such as dampening housings—can mitigate the effect of these oscillations on image quality. Many rUAVs have an integrated damped gimbal that simultaneously provides this needed stabilization as well as providing the ability to orient the camera towards a target. Although fwUAVs can support heavier, more capable imaging systems, existing offerings do not typically include camera stabilization or positioning capabilities. Infrared cameras capable of thermal imaging can be mounted on both fwUAVs and rUAVs. These cameras generally have lower image quality (e.g. image resolution, frame rate, etc.) exacerbating any limitations imposed by the UAV itself.

Real-time control

As fwUAVs require forward relative velocity to maintain altitude, it is difficult for an operator to directly control the fwUAV to obtain a specific image. Rather, fwUAVs need flight planning and execution software. Although the flight path of the fwUAV can be modified while the fwUAV is in the air, directing the fwUAV to obtain a specific image during flight can be difficult. In contrast, rUAVs can move in any direction and can hover, enabling a minimally trained pilot to position the rUAV to get the desired image. Consequently, rUAVs flight paths can be modified much more quickly and precisely to react to what the pilot wishes to explore; in this paper we refer to this as real-time control. This allows rUAVs to perform a more thorough search of a given area while fwUAVs are less amenable to human controlled, real-time changes in flight path.

Technology roadmap for deploying UAVs for SAR

In addition to understanding the practical limitations of currently available fwUAVs and rUAVs, we must look toward the future to identify the role that the SAR community must play in UAV development so that they are best positioned to capitalize on this new technology. The UAV industry is growing very quickly with large numbers of new entrants driving down costs and maintaining a highly competitive marketplace ("Commercial drones are the fastest-growing part of the market | The Economist," 2017). As the industry continues to serve increasingly demanding customers with capital-intensive applications such as mining, agriculture, real-estate development, and infrastructure maintenance, UAV hardware will improve along many of the same dimensions that those in wilderness search and rescue require: flight speed, flight duration, range, and image quality (Cohn, Green, Langstaff, & Roller, 2017).

Despite these advances, these systems will not be immediately suitable for applications in aSAR as each new application presents unique software needs. Without dedicated software that spans mission planning to UAV control to specialized image acquisition, the ultimate impact of UAVs on SAR will be limited.

It is the responsibility of the SAR community to identify the most important software needs for UAVs and begin working with UAV developers to integrate their perspectives into technology development plans. Engaging hardware companies in these conversations early, while they are identifying which markets to enter, is critical to ensuring that UAVs ultimately serve the needs of SAR.

We have identified four distinct, platform agnostic, areas of software innovation that, if implemented, would enable UAVs to be much more effective for aSAR. These are 1) creation of optimized flight paths, 2) launch and landing site selection, 3) enabling rescuers to examine areas of interest more closely, and 4) enhanced image acquisition tailored towards identifying lost subjects.

Creation of optimized flight paths based on search specific information

Synthesizing data from multiple sources to help identify where to conduct the aerial search and determine the exact flight path for the UAV will allow SAR teams to more effectively use their UAVs for aSAR. These inputs include information specific to the case at hand such as the last known position of the subject, the physical appearance of the subject, demographic information which can help predict expected behavior, and any unique information about the subject. Maps (topographic, vegetation, roads) and imagery (aerial images, trail images) provide a basis for understanding where the subject may travel and how to plan the search. The combination of these datasets along with heuristics from SAR experts can be used to produce a Probability of Detection (PoD) map for aSAR(Twardy et al., 2012). Most often, this has been performed manually, qualitatively, and is guided by intuition and expertise gained from years of experience. We believe that software can augment, if not fully automate, this process to enable rapid and accurate identification of regions of interest where the subject is most likely to be found. Fully automated generation of the PoD map is less time consuming than manual or semi-automated generation of these maps and standardizes the process across search teams allowing searches to be compared and shared across teams.

The U.S. Coast Guard has already implemented an analogous system for water based searches. The system, known as Search and Rescue Optimal Planning System (SAROPS), is designed to aid Coast Guard rescue coordinators in planning and executing searches for people and vessels lost at sea. It has been in operation since March 2007 and consists of two major components, an environmental data server that provides inputs such as winds, currents, and visibility, and a simulator and planner that produces probability distributions for search object location and recommends optimal search plans. SAROPS is an operational tool with a proven track record in maritime search and rescue operations (Metron Inc.). The success of SAROPS serves to demonstrate the benefits and technical feasibility of an analogous system for UAVs in search and rescue.

The proposed algorithm would combine the Probability of Detection map with information specific to the UAV to produce a flight path and image acquisition plan designed to most optimally search the area. This will be based on constraints imposed by the maximum speed, image quality, and flight duration of the UAV along with the spatial resolution, frame rate, sensitivity, and field of view of the imaging system (**Figure 2**). This process can be automated and extended to consider the use of multiple UAVs or to coordinate with ground SAR teams.

As an example, consider a SAR team that desires a particular image resolution and frame-to-frame overlap. Using the equations in Appendix A, these values will set the flight altitude and flight speed. In turn, these will determine the rate at which the UAV can cover an area. We can then formulate the problem as a series of nodes connected by weighted edges, where the value of each node is defined by regions of increased probability of detection and edge weights are dictated by the time required to traverse between these nodes. Over a set period of time, we can use a modified A* or similar search algorithm to maximize the probability of detection, which is found by integrating over the probability of detection distribution. Finally, this will generate a flight path that the UAV can execute.

This general framework based upon combining many sources of data in an intelligent manner can be extended to build software to address each of the other critical areas we have identified.

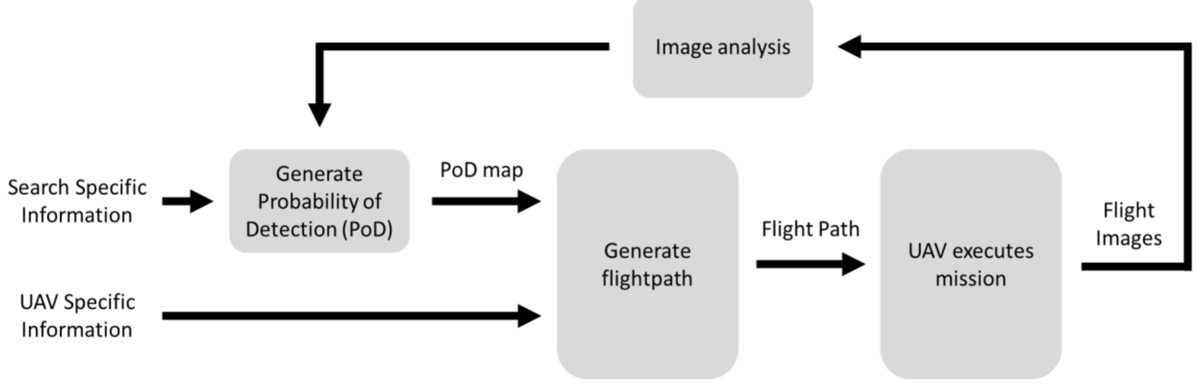

Figure 2. Optimized UAV flight paths. *First the probability of detection is generate based upon search specific information. This is then combined with the UAV specific information to generate a flight path that maximizes the likelihood of detection. As the UAV executes this flight path, it feeds the flight images, along with updated search*

information, to update the probability of detection and thus the flight path. This feedback is performed continuously to generate the up-to-date best flight path for the UAV.

Optimal site selection for launch and landing plans in rugged or dense terrain

Search missions often take place in undeveloped, wilderness areas. Heavy brush and trees, nearby bodies of water, and mountainous regions can limit access to open flat regions. Unsurprisingly, launch and landing represent the highest potential for catastrophic UAV failure. Identifying a launch and landing site that balances risk to the UAV with rapid deployment and maintaining a large range of communication is key to the success of UAVs for SAR.

While rUAVs are easily capable of launching and landing vertically, fwUAVs, due to their airplane-like flight dynamics, typically cannot launch or land vertically. Despite these differences, a common framework can be developed for identifying optimal launch and landing sites. Similar to the software above, this takes as input (1) search specific information, (2) maps and aerial imagery, (3) UAV specific information, and (4) probability of detection map.

This can be seen as an extension of the software outlined above to identify the UAV flight path as the launch and landing site serve as the beginning and end of the flight path. We present one possible implementation of this. The SAR team would first set a tolerable risk threshold for both launch and landing. From this, all suitable launch and landing zones within a specified area would be identified. These are determined by the capabilities and type of the UAV. For example, rUAVs would have significantly more potential launch and landing areas. From here, these zones would be ranked based upon delay to deployment, allowable range of communication, and safety to the UAV team, among other factors. Performing an optimization over these factors would produce an optimal flight path with a suggested launch and landing zone.

Additional software can be developed to mitigate the risk of launch and landing even in the case of challenging terrain, especially for fwUAVs. During launch and landing, the system would select a heading into the wind to allow for a steep angle of attack. Alternatively, by forcing the UAV into a stall shortly before landing, the UAV would lose the majority of its forward momentum, allowing it to land in a small opening without significant impact. Such systems have not yet been built or integrated into commercial UAVs and would require significant engineering before widespread deployment.

Synthetic hovering: enabling examination of areas of interest more closely

While traversing a flightpath, regions of interest may be identified. It can be helpful to take observations of that region from multiple perspectives and at various time points. A single observation of the region of interest can be insufficient due to obstructions, variations in lighting conditions, and degraded image quality. Multiple observations provides more information which increases confidence in identifying the presence of a subject in the searched region. Therefore, it is critical that any aSAR system, regardless of type, can perform longitudinal observations of a particular region from different perspectives.

Hovering—the ability to remain stationary midflight—is one approach used during traditional aSAR to obtain multiple observations of a particular region. Helicopters and rUAVs can hover naturally, but fwUAVs cannot hover because they rely on forward motion to remain airborne. This limitation has slowed the adoption of fwUAVs in SAR and must be ameliorated to help increase the versatility of these systems. A combination of an appropriately designed flight path, responsive camera and gimbal control, and advanced image reconstruction software can help emulate hovering from the point of view of the end user.

The main inputs to this synthetic hovering system are (1) a location of interest, (2) a set of desired perspectives, (3) search specific information, (4) maps and aerial imagery, and (5) UAV specific information.

The first component of this system is close integration of the flight control system, which determines and executes the flight path, and the control system for the camera and gimbal, which controls the orientation and field of view of acquired images. As the fwUAV circles the search region, the gimbal control system would ensure that the area of interest always remains within the field of view (**Figure 3a**).

Images acquired from multiple perspectives and information on from where the images were taken would be used to produce a 3D reconstruction of searched region. Recently, 3D reconstruction techniques have advanced dramatically and calibration free methods would be well suited to the task(Yu, Mcmillan, & Sturm, 2010). While a single image may not capture motion, subtle changes in an image can be extracted using robust algorithms that are now straightforward to implement (Benezeth, Jodoin, Emile, Laurent, & Rosenberger, 2008) (**Figure 3b**).

A system designed to present the end user with a continuously updating 3D model captured from a fwUAV would greatly aid in reexamination of a search region. This would be straightforward to implement using existing technology and capture much of the benefit that rUAVs provide due to their unique ability to hover.

Further, while not strictly necessary for rUAVs and helicopters to hover, synthetic hovering offers benefits beyond traditional hovering. Traditional hovering observes a region from a static perspective over multiple time points. Therefore, it can still be affected by occlusion of the target. Because synthetic hovering also varies the perspective, it can overcome these challenges. Given this, synthetic hovering techniques should be applied to both rUAVs and fwUAVs.

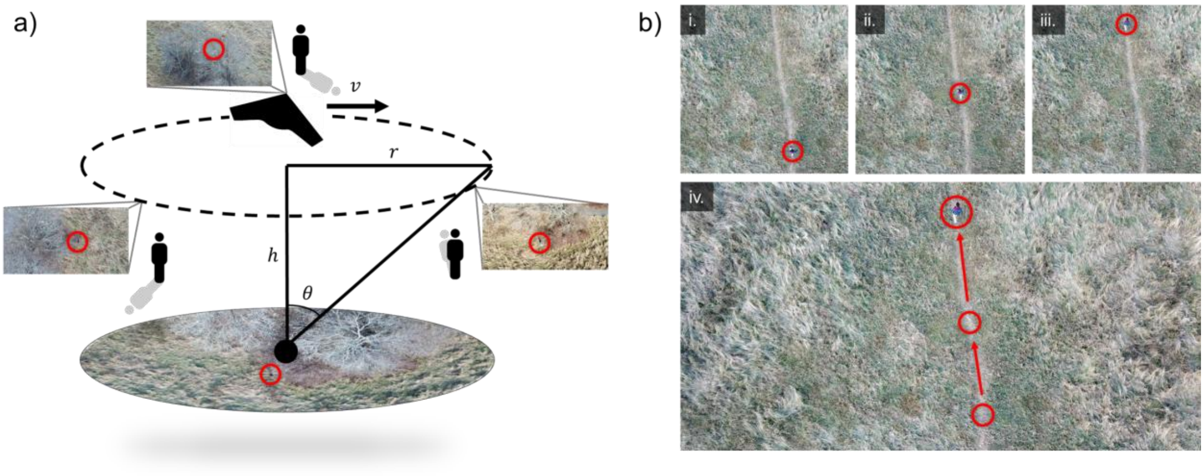

Figure 3. Synthetic hovering. a) *By circling a region of interest, multiple perspectives can be obtained. These multiple images, especially when reconstructed into a single larger image, can allow searchers to overcome obstructions to identify the target.* ***b)*** *Identifying the subject from individual static images can be difficult due to lack of contrast or too wide of a field of view. Multiple images of the same area (i-iii) can indicate the presence of the*

subject by highlighting regions where the image varies in time (iv). Further observation can indicate the direction and speed of travel of the subject.

Enhanced image acquisition to increase probability of human subject detection

In order to successfully complement SAR efforts, the information found in the images acquired by a UAV must be made readily accessible to search teams. Software designed specifically for this purpose can leverage GPS information to allow the user to view recorded images on a map. Regardless of how the images are acquired, the images must be presented to the user with continuity between adjacent regions and redundant images made available for inspection. Extensive field testing indicates that presenting image mosaics from video is more useful than simply viewing the original video (Goodrich et al., 2008). Furthermore, the user must be able to search these images based on both GPS coordinates and objects found within the images (**Figure 4a**).

Recent advances in image identification and classification algorithms, in particular those based on machine learning, allow software to discern the environment, local geographical features, particular evidence left by a subject (e.g. discarded jacket), and the subject itself from within these images (Ofli et al., 2016).

The acquired images must be stable and free from blurriness associated from the motion of the UAV. Today many fwUAVs are unable to acquire stable video as their cameras are rigidly affixed to the body of the UAV. This reduces the probability of detection as minor features may not be resolvable within these images. Hardware solutions, such as gimbals and vibration dampening devices, have not yet been widely integrated into fwUAVs. In the near term, stabilization and motion blur reduction software should be incorporated into the image acquisition and processing workflow (**Figure 4b**).

Information about the missing subject, such as clothing, can be incorporated into image processing algorithms to enhance images. Drawing the attention of an observer to a particular region of an image based on particular patterns or colors could improve the probability of detection, especially in the case of occlusion or otherwise limited visibility. Filtering or other color-based manipulations should be performed in the HSV color space as the hue and saturation channels are less sensitive to variations in lighting conditions compared to the traditional RGB color space (**Figure 4c**).

Finally, since images will be acquired with some overlap and some regions may be examined repeatedly, software tools must be developed to efficiently incorporate all of the acquired information at each location. Redundant image acquisition provides advantages such as multiple perspectives to view occluded areas, the ability to assess changes over time, and potentially improved lighting depending on time of day and weather conditions. Furthermore, redundant images can be combined to provide enhanced image resolution, increasing the probability of detection (Liu, 2004).

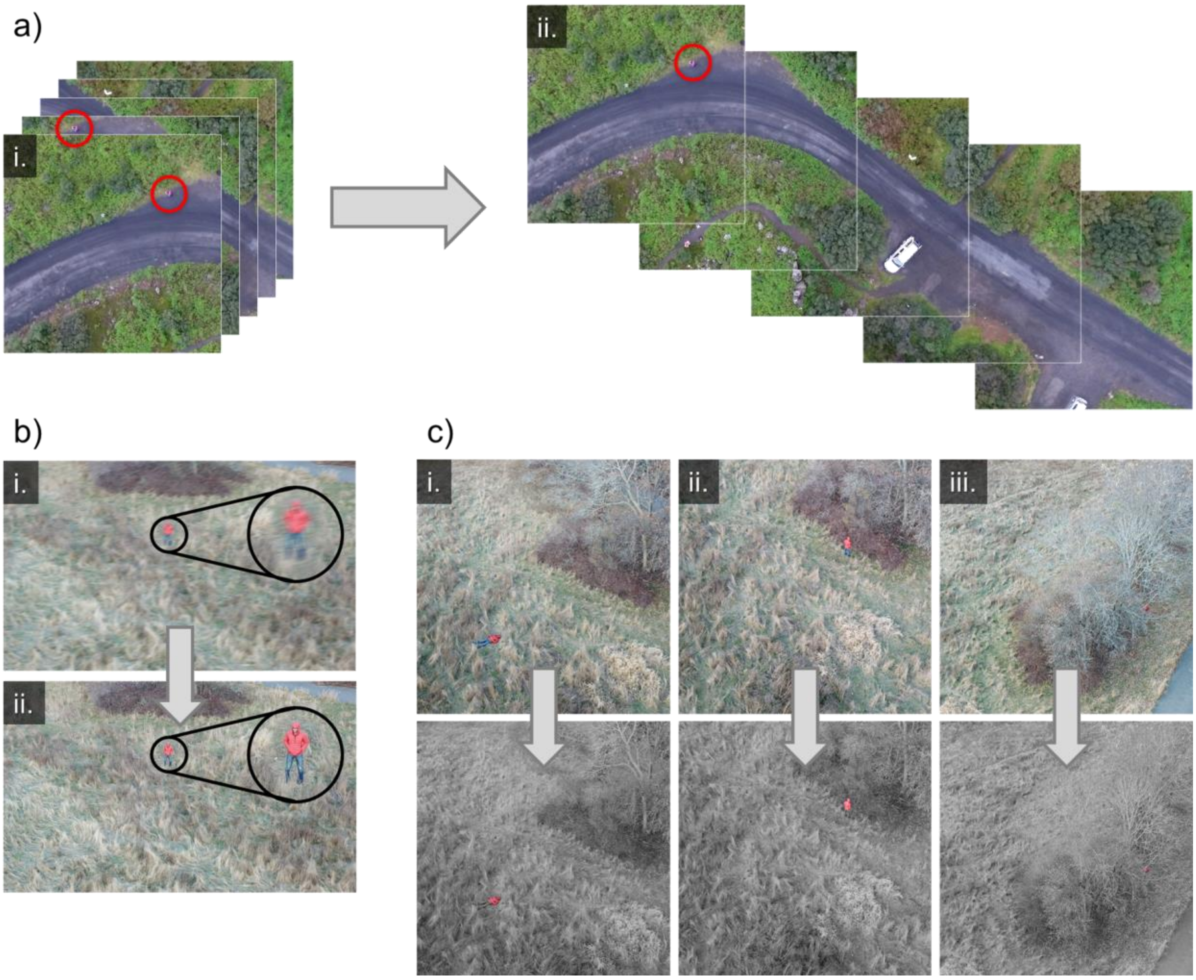

Figure 4. Enhanced images for improved subject detection. a) *Video frames acquired sequentially increase the confidence of detection of a subject. Viewing these images sequentially, as in (i), can make it difficult to identify and track a subject. In contrast, viewing images as a tiled mosaic, as in (ii), allows common features to be co-registered between images.* ***b)*** *Images acquired from a moving UAV may be corrupted with motion blur. Sharpening and motion blur compensation techniques can improve the image. This increases confidence when attempting to identify the lost subject.* ***c)*** *Search specific information, such as the color of the subject's clothing, can be used to enhance or filter images. In this example, a filter is applied to each image that converts everything to greyscale except for shades of bright red. This allows rapid identification of the lost subject, even when occluded by trees (iii).*

Conclusion

Aerial SAR effectively augments ground SAR by enabling searches over larger and more difficult to access areas. Traditionally performed with helicopters, its use is limited to well-resourced teams and the direst of circumstances where its cost is justified. UAVs can capture many of the benefits of traditional aSAR while lowering costs by two to three orders of magnitude thus allowing UAVs to be deployed more readily.

rUAVs can make an immediate impact on how SAR is conducted today which have already benefited from significant commercial development. rUAVs can launch and land nearly anywhere, are often equipped with image stabilizing gimbals that improve image quality, and are simple to deploy and operate. Further, they can be deployed without significant additional software development because they are amenable to real-time control.

However, as fwUAVs continue to benefit from additional development driven by a wide range of industries with common hardware needs, their capabilities will better complement gSAR because of their ability to quickly survey large areas with better imaging systems.

For UAVs to reach their full potential, the SAR community must ensure that the necessary accompanying software is built. We have identified four software areas that, if developed, will increase the effectiveness of UAVs for SAR. This software must 1) create optimized flight paths, 2) intelligently select launch and landing sites, 3) enable rescuers to examine areas of interest more closely, and 4) enhance image acquisition to assist in identifying lost subjects.

The community will be instrumental in advancing UAVs for SAR

As the hardware for fwUAVs continues to be developed by other industries, the SAR community must invest resources into software to suit the unique needs of the field. These software tools can be platform agnostic and therefore maintain interoperability between different UAV systems. This will be important as many suitable commercial fwUAVs enter the market.

Despite the fact that the ideal fwUAV may not be immediately available, it is important to begin implementation and testing of flight paths, image acquisition, and subject identification algorithms using fwUAVs. This will provide valuable feedback to both the SAR and UAV community on how to guide future improvements in fwUAV capabilities.

Guidelines of best practices for using UAVs for SAR must be established before meaningful deployment can take place. The experimentation and testing performed by a few SAR teams can greatly benefit others around the world if the information is effectively organized and disseminated. Robert Koester’s book is an exemplary resource for gSAR techniques as it is based on empirical data gathered by many teams in diverse environments (Koester, 2008). Moreover, Koester has begun taking initial steps by experimentally determining optimal UAV flight parameters (e.g. speed, altitude) across various terrains (Knight, 2017). The impact of this work and others could be amplified by sharing the data and findings in a public repository of shared knowledge accessible to SAR teams around the world.

As guidelines begin to be supported by empirical evidence, they will form the basis for future fwUAV hardware development. The SAR industry can work with commercial partners, many of whom have already demonstrated interest in the field, to develop UAVs tailored specifically for their unique needs.

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Ashvin and Jacob began their work in SAR with a vision to bring fixed wing UAVs to wilderness search and rescue. After initial hardware and software development, field-testing in Iceland with the generous support of MIT and ICE-SAR, and a subsequent presentation at the RESCUE 2016 conference, they chose to share their findings with the community. The technical capabilities of UAVs will continue to improve as the industry moves forward. The SAR community must work with industry to foster the development and dissemination of this new technology. They intend to remain accessible as a resource to those interested in learning from our experiences. Please contact them with your questions, ideas, or connections. Hopefully this work inspires others to begin work developing, testing, and deploying UAVs for SAR.

Abbreviations

SAR	search and rescue
aSAR	aerial search and rescue
gSAR	ground search and rescue
UAV	unmanned aerial vehicle
fwUAV	fixed wing unmanned aerial vehicle
rUAV	rotary unmanned aerial vehicle

References

Benezeth, Y., Jodoin, P. M., Emile, B., Laurent, H., & Rosenberger, C. (2008). Review and evaluation of commonly-implemented background subtraction algorithms. In *2008 19th International Conference on Pattern Recognition* (pp. 1–4). IEEE. http://doi.org/10.1109/ICPR.2008.4760998

Cohn, P., Green, A., Langstaff, M., & Roller, M. (2017). Commercial drones are here: The future of unmanned aerial systems | McKinsey & Company. Retrieved March 8, 2018, from https://www.mckinsey.com/industries/capital-projects-and-infrastructure/our-insights/commercial-drones-are-here-the-future-of-unmanned-aerial-systems

Commercial drones are the fastest-growing part of the market | The Economist. (2017). Retrieved March 8, 2018, from https://www.economist.com/news/technology-quarterly/21723003-most-drones-today-are-either-cheap-toys-or-expensive-weapons-interesting

DJI. (2018). Phantom 4 - DJI's smartest flying camera ever. Retrieved August 1, 2018, from https://www.dji.com/phantom-4

Federal Search and Rescue Activities. (2013). Retrieved March 8, 2018, from http://www.oag-bvg.gc.ca/internet/English/parl_oag_201304_07_e_38192.html

Fundacion EcoMinga. (2016). How to land a fixed-wing drone in a dense forest | Fundacion EcoMinga. Retrieved August 2, 2018, from https://ecomingafoundation.wordpress.com/2016/10/12/how-to-land-a-fixed-wing-drone-in-a-dense-forest/

Goodrich, M. A., Morse, B. S., Engh, C., Cooper, J. L., & Adams, J. A. (2009). Towards using Unmanned Aerial Vehicles (UAVs) in Wilderness Search and Rescue: Lessons from field trials. *Interaction Studies*, *10*(3), 453–478. http://doi.org/10.1075/is.10.3.08goo

Goodrich, M. A., Morse, B. S., Gerhardt, D., Cooper, J. L., Quigley, M., Adams, J. A., & Humphrey, C. (2008). Supporting wilderness search and rescue using a camera-equipped mini UAV. *Journal of Field Robotics*, *25*(1–2), 89–110. http://doi.org/10.1002/rob.20226

Heggie, T. W., & Amundson, M. E. (2009). Dead Men Walking: Search and Rescue in US National Parks. *Wilderness & Environmental Medicine*, *20*(3), 244–249. http://doi.org/10.1580/08-WEME-OR-299R.1

Heggie, T. W., & Heggie, T. M. (2009). Search and Rescue Trends Associated With Recreational Travel in US National Parks. *Journal of Travel Medicine*, *16*(1), 23–27. http://doi.org/10.1111/j.1708-8305.2008.00269.x

Kentucky Emergency Management. (2014). **SAR Field Search Methods* Search Techniques Used by Trained Teams in the Field*. Retrieved from https://kyem.ky.gov/Who We Are/Documents/SAR Field Search Methods.pdf

Knight, R. (2017). Drones and First Responders: Help From Above - Inside Unmanned Systems. Retrieved March 10, 2018, from http://insideunmannedsystems.com/drones-first-responders-help/

Koester, R. J. (Robert J. (2008). *Lost person behavior : a search and rescue guide on where to look for land, air, and water*. DbS Productions.

Liu, C. (2004). On Bayesian Adaptive Video Super Resolution. *IEEE Transactions on Pattern Analysis* *and Machine Intelligence*, *26*(2), 0_2-0_2. http://doi.org/10.1109/TPAMI.2004.1307308

Lockheed Martin. (2005, February 4). UAV arresting hook for use with UAV recovery system. Retrieved from https://patents.google.com/patent/US7143976

Metron Inc. (n.d.). Simulator and Search Planner for the USCG SAROPS Search And Rescue Optimal Planning System. Retrieved from http://www.sarapp.com/docs/SAROPS Description.pdf

Nakamura, M. (1999). Air Foil. Retrieved from http://web.mit.edu/2.972/www/reports/airfoil/airfoil.html

Ofli, F., Meier, P., Imran, M., Castillo, C., Tuia, D., Rey, N., … Joost, S. (2016). Combining Human Computing and Machine Learning to Make Sense of Big (Aerial) Data for Disaster Response. *Big Data*, *4*(1), 47–59. http://doi.org/10.1089/big.2014.0064

Priority 1 Air Rescue. (n.d.). Retrieved from https://priority1airrescue.net/

Rees, M. (2016). Lehmann Aviation Announces New Drones for Professional Mapping Applications. Retrieved August 1, 2018, from http://www.unmannedsystemstechnology.com/2016/07/lehmann-aviation-announces-new-drones-for-professional-mapping-applications/

Tomazin, I., & Kovacs, T. (2003). Medical Considerations in the Use of Helicopters in Mountain Rescue. *High Altitude Medicine & Biology*, *4*(4), 479–483. http://doi.org/10.1089/152702903322616236

Twardy, C. R., Jones, N., Goodrich, M., Koester, R. J., Cawi, E., Lin, L., & Sava, E. (2012). MapScore: A Portal for Scoring Probability Maps Static Models of Lost Person Behavior. Retrieved from http://sarbayes.org/wp-content/uploads/2012/08/MapScorePoster_MORSS2012.pdf

Yu, J., Mcmillan, L., & Sturm, P. (2010). Multi-Perspective Modelling, Rendering and Imaging, *29*(1), 227–246. http://doi.org/10.1111/j.1467-8659.2009.01587.x

Appendix A: Formulas

Variables

System inputs	
UAV, maximum flight speed	v_{max}
UAV, minimum flight speed	v_{min}
Camera, resolution	res_x, res_y
Camera, angular field of view	α_x, α_y
Camera, image acquisition time interval (shutter speed)	T_{acq}
System outputs	
Flight speed	$v(t)$
Flight altitude	$h(t)$
Imaging system: frame-to-frame overlap	O
Imaging system: field of view per pixel	FOV_x', FOV_y'
Imaging system: field of view, total	FOV_x, FOV_y

Equations

Convert angular field of view and flight altitude into image coverage (field of view). This equation is helpful to understand how much ground a single image will cover when taken at a given height. Assumption: the terrain is flat.	$FOV_i = 2 * h * tan(\frac{\alpha_i}{2})$
Convert angular field of view and desired image coverage (field of view) to height. The equation is useful when deciding how high a UAV should fly to achieve a particular image coverage with a given camera.	$H = \frac{FOV_i}{2 * tan\left(\frac{\alpha_i}{2}\right)}$
Convert image resolution, angular field of view, and desired pixel size to height. This equation is useful when deciding how high to fly to achieve a particular pixel size for a given camera. This is important since identification of an object requires it to occupy many pixels.	$H = \frac{FOV_i' * res_i}{2 * tan\left(\frac{\alpha_i}{2}\right)}$
Convert angular field of view, height, image acquisition interval, and desired overlap fraction to flight speed. This equation is helpful when setting the flight speed to achieve a particular amount of image to image overlap. If the necessary velocity is greater than the maximum velocity of the UAV, consider acquiring images less frequently or allowing more image-to-image overlap. If the necessary velocity is less than the mimimum velocity of the UAV, consider doing the opposite.	$v = \frac{FOV_y * (1 - O)}{T_{acq}},$ $v_{min} <= v <= v_{max}$

Appendix B: Explanation of key terms

Ground search and rescue (gSAR)	Search and rescue performed primarily by persons traveling on foot and communicating primarily via radio
Aerial search and rescue (aSAR)	Search performed with the assistance of a flying vehicle, such as a helicopter, that provides the ability to search a large area more quickly
Rotary UAV (rUAV)	A UAV with vertically oriented propellers that generates lift and accelerates via the speed and pitch of the propellers
Fixed wing UAV (fwUAV)	A UAV with an airfoil and one or more horizontally oriented propellers that generates lift by gliding through the air