USAGE OF UNMANNED AERIAL VEHICLES IN SEARCH AND RESCUE OPERATIONS

Lappeenranta-Lahti University of Technology LUT

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ABSTRACT

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This Thesis investigates the present integration of UAVs in SAR operations. Considering the findings from modern research papers analysis, it describes the nowadays situation in SAR department, existing methods and solutions for UAV usage and proposes the future development of the SAR operations mechanisms.

Through the study and comparison of available and upcoming approaches, the thesis summarizes and generalizes the many methods into universal classification model. This way the thesis aims to introduce to the reader the key trends of UAV development in the field of SAR operations. In addition, it underscores the main difficulties of drones integration in SAR, providing a deeper understanding about the arising challenges.

Finally, the study presents the examined techniques in a form of sub-chapters, which are organized into two main groups by their function - Interactive or Analytical. Furthermore, it introduces the present UAV models and their topological classification. By doing so, the paper not only provides the valuable information and insights about UAVs, but also proposes the future development of UAV technology in SAR operations, finally resulting in a contribution to the future research in the field.

SYMBOLS AND ABBREVIATIONS

Dimensionless quantities

R	Speech quality level
I_d	Delay effect
$I_{e,eff}$	Low bit-rate coding effect

Abbreviations

ABT-YOLO You Only Look Once algorithm integrated with AFPN, BiFormer module and TSCODE

ACA Ant Colony Algorithm

AFPN Asymptotic Feature Pyramid Network

AP Access Point

BER Bit Error Rate

BIM Building Information Modeling

CNN Convolutional Neural Networks

ELT Emergency Locator Transmitter

EU European Union

FFP2 filtering facepiece 2

FwUAV Fixed wing UAV

hUAV Helicopter UAV

HyUAV Hybrid UAV

IAMSAR International Aeronautical and Maritime Search and Rescue

MANET Multi-hop Mobile Ad-hoc Network

MrUAV Multirotor UAV

MTSP Mass Travelling Salesman Problem

NIC Network Interface Controller

PPE Personal Protective Equipment

RCC Rescue Coordination Centre

RCT Randomized controlled trial

RFC Random Forest Classifier

RGB Red Green Blue

RSC Rescue Sub-Centre

SAR Search and Rescue

SfM Structure from Motion

SQL Speech quality level

STBC Space-Time Block Code

SURF Speeded-up Robust Features

TSCODE Task- Specific Context Decoupling

UAV Unmanned Aerial Vehicle

VTOL Vertical Takeoff and Landing

WRN Wireless Relay Networks

YOLO You Only Look Once algorithm

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1 INTRODUCTION

Nowadays our life is supported by various devices, and the new soon might enter this list on a common basis - UAVs. UAVs are a universal tool, which can be used for a huge variety of tasks. This Thesis studies the UAV implementation in SAR operations based on the literature review. Often SAR operations are full of dangers and risks for not only victims of a catastrophe, but also for the rescue team members. Unfortunately, the technological advancement brings new challenges and threats, making operations to become more dangerous. However, UAVs can be integrated in the process to enhance the overall performance and keep people safe.

At the moment, it is an absolutely new field to research, and much development is now ongoing there. However, several main branches were discovered based on UAV capabilities: site analysis, observation, communication and supply. UAVs can be implemented in SAR operations to provide new approaches to fulfil these four purposes, resulting into overall performance improvement. Most of research is focused on these approaches.

Despite the extra abilities the drones bring to the SAR operations, they still can not manage themselves well, and that brings the situation to the introduction of another new field - UAV-supported rescue teams and UAV management. UAVs themselves are not able to enhance the outcomes. In the same time, the four main tasks presented earlier take a lot of time and effort to complete manually. However both UAVs and rescue teams can work together, benefiting each other and dramatically improving the results of an operation.

Finally, based on all the issues, this thesis aims to study the state of UAV technology development, mainly identify the key trends of the research, examine and generalize the present inventions and classifications, find out how and why UAVs are used in SAR operations nowadays. There are many research papers available at the moment on the topic of UAV development, and, in order to make the research compact and up-to-date, all trends are observed on the basis of the recent years publications. Hence some of the other technologies might not be mentioned here, but, as stated above, the main target is to give a general observation of the situation, so it is negligible.

2 Current state of Search and Rescue operations

This chapter tells about SAR operations definition, their usual structure, the difficulties occurring and overall performance.

2.1 SAR operations: Definition

Search and Rescue operations can be defined differently, depending on their scale. For example, according to the European Commission, there are two definitions, and both mean different levels of operations - local:

> “In the global context: operation to render assistance to persons in distress at sea regardless of the nationality or status of such a person or the circumstances in which that person is found in accordance with the applicable Maritime Law and Conventions. (Comission 2023)”

And cross-state cooperation:

> “In the European Union (EU) context: operation of EU Member States to render assistance to any vessel or person in distress at sea regardless of the nationality or status of such a person or the circumstances in which that person is found in accordance with international law and respect for fundamental rights. (Comission 2023)”

So, in general, Search and Rescue operation is an operation, where the group of people is trying to search for and rescue victims of any kinds of catastrophes, from natural disasters to acts of terrorism, as fast as possible. These operations can be performed by anyone who is willing to help. Rescue of anybody automatically becomes a SAR operation, only the scale and, perhaps, importance differs.

2.2 SAR operations: Objectives and Structure

So, the whole system is designed to reach and improve the overall results of operation. All SAR operations have, in general, common goals. They might change depending on the case. Here is the list stated in International Aeronautical and Maritime Search and Rescue (IAMSAR) manual (Organization 2006):

- Minimize loss of life, personal injury, and property loss or damage;

- Minimize time spent searching for persons in distress by using technology, research and development; education, regulation, and enforcement;
- Improve safety so that the number of distress events is reduced;
- Improve co-operation between aeronautical and maritime SAR authorities;
- Receive, validate and transmit distress notifications;
- Co-ordinate SAR responses;
- Conduct SAR operations;

Following these targets, the SAR operation is managed and planned. Management and preparations of the whole operation is divided in micro managements of each subsystem. These subsystems together form a structure of SAR operation. These can differ from case to case, but generally the system is organized as presented in the table 1:

General Levels	**General Functions**
SAR Co-ordination	Management
SAR Mission Co-ordination	Mission Planning
On-scene Co-ordination	Operational Oversight

Table 1: SAR operation management structure (Organization 2006)

Each department plays it's own role here, so a high level of cooperation is needed for a successful operation. Hence communication is a vital part of the process. With such structure, the communication model is as presented on the figure 1:

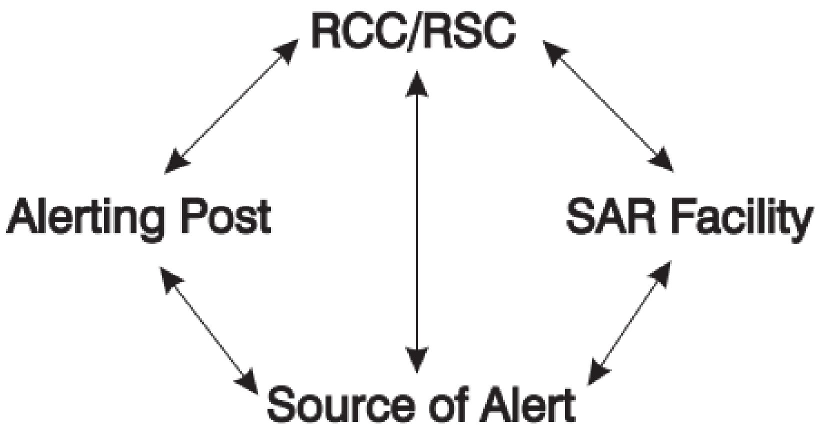

Figure 1: SAR operation communication scheme (Organization 2006)

So, the source of alert can be investigated by the Rescue Coordination Centre (RCC) or Rescue Sub-Centre (RSC) directly, either by local Alerting Posts and SAR Facilities. Anyone who or anything which exchanges such information to RCC/RSC is considered as an Alerting Post. Next this information is shared with other departments according to the graph 1. Good communication allows to locate targets on the site. Obviously, ability of locating is essential, as it's the main way to rescue survivors faster and avoid other possible casualties. For instance, most civil aircraft and maritime vessels are required to carry Emergency Locator Transmitter (ELT). These ELT's are a valuable source of information for the rescue teams, which dramatically decrease the needed searching time.

So, together communication and target localization form SAR operation coordination, where various agreements, legislation and other organizational decisions are applied. The common structure of it is presented earlier in the figure 1.

2.3 SAR operations: Nowadays issues

As UAV only start to be implemented in the SAR operations worldwide, most of the duties are still done by manual labour, therefore the quality and accuracy of the results are subject to skills and experience of the rescue team. So, the list of skills and qualifications needed for a position in a rescue team was developed (Organization 2006):

- Ability to notice problems and find a solution fast;
- Ability to analyze the situation in big scales, taking almost all information into account;
- Ability to cooperate and communicate with teammates effectively;

And other skills beneficial to the duties assigned to different roles. There are also personal characteristics taken into account, like persistence, empathy, honesty, etc, but also experience. However, as stated in Lance Piatt's article (Piatt 2023), the efficiency still needs to be increased, and here are the main issues:

1. Incorrect practicing or training
2. Communication problems
3. Limited time
4. Fatigue
5. Limited resources

Firstly, the inadequate training leads to ineffective implementation of different devices on the SAR operation site, non-optimized team work, sometimes resulting is small conflicts between the team members. All these issues can even lead to life or death situations, that could have been avoided if true guidelines had been followed.

Secondly, communication problems. These can occur partly because of the issue just above, but not always. In order to make communication better, the following standards are established and fixed in the IAMSAR manuals (Organization 2006):

1. Priority of a message. Usually signals from the source of alert have the highest priority.

2. Reliability of equipment. Equipment must be checked before any SAR operation.

3. Availability of equipment. Each department involved in the operation must have a direct access to use communication equipment.

However, the human factor is always present, and some of these can be just forgotten for a moment, or not followed in a correct way. The rescue team is usually experiencing medium to high stress levels even with training and experience, time to time causing delays, lack of information and other issues.

Thirdly, time limitations. People stuck under the debris or suffering from the smoke, hunger, etcetera, often can not wait the rescue team for a long time. For example (Tipton et al. 2022), people floating in water can not remain alive for longer than 2.5 - 4 hours (water temperature 10^{o}C), so the marine rescue team must locate all the victims in that short period of time. During a clear day it is a far easier problem than at night or during storm, heavy rain and so on. It is difficult to successfully complete all the steps with such time constraints. It can be even harder if also having problems in other fields.

Fourthly, fatigue. Fatigue is also a critical obstacle during operation. After long hours of searching, people might and usually feel exhausted, or, rarer, hopeless. Each person must follow the healthy lifestyle in order to push the limits, however often some people might not. This can also be caused by emotional tiredness, like stress or over-concentration.

Finally, lack of resources. Resources are protective equipment, money, available vehicles, machines, number of personnel and so on. There may be a shortage of any due to insufficient funding, both from public or private sectors, spending and using the gear in inappropriate way, underestimating the possible risks. The shortage of resources leads to long and inefficient operations, which also might put the team members at higher risks and more dangerous situations.

2.4 SAR operations: Conclusion

All in all, nowadays SAR operations are still being improved and standardised worldwide, as well as the rescue departments. Many new systematic solutions are developed to enhance interconnection between the general levels of SAR team, make operations more efficient. However, there are not enough of automatizing and new technologies used on the sites. Hence all the routine is being done by people, leading to the lack of personnel, exhaustion, stress, work quality reduction, etc. So, some of the inventions SAR operations can be improved by are UAVs, as these can, for example, help to analyze the site, deliver goods. They can dramatically enhance the SAR operation performance, therefore people should take a look, test and try them in a real case.

3 Current UAV applications in SAR operations

This chapter tells about the existing practices of using UAVs in SAR operations and purpose why drones are used. It also explains main difficulties occurring while using UAVs, the advantages and drawbacks of the described methods.

3.1 Function 1: Analytical - analysis, modelling and on-site observations

To begin with, the first step of any SAR operation is to examine the site (Organization 2006). Usually the sites left after the catastrophes are extremely dangerous, especially in urban areas due to additional risks of structure collapse. Hence any extra movements or actions can lead to even worse results. However, UAVs can be used for Analysis and Modelling of the SAR operation site. Such analysis can provide general information about the obstacles and disasters existing in the area, as well as additional information about the situation continuously, decreasing the number of possible casualties during the operation. Moreover, such observation can lead to investigation of the potential spots where people might be trapped, the new paths, which can be used to conduct the operation more effectively. Here is a real example, a 2013 Lushan earthquake:

> "When encountering a natural disaster such as an earthquake, the collapsed building in the residential area becomes the obvious target location for the SAR team to operate the mission. Therefore, the developed UAV system was applied to search the collapsed building for rescuing the victims in the mountain areas, which ended up with a successful identification rate of 80%. (Hailong. 2023)"

3.1.1 Area observation and simulation: SfM

There are several methods to conduct area examination using UAVs. One of them is presented in the survey (Hailong. 2023) - Structure from Motion. This method uses a 3D point cloud to make a 3D model out of it. The cloud is approximated from the sequence of digital images or a video stream, based on the UAV's camera motion. Next the special software, like PhotoScan, MicMac, MeshLab, etc is used to build a 3D model of an area from the 3D point cloud. This user-friendly 3D model can already be used by a SAR team to plan the operation faster. It can also be rendered in programs like Blender for better quality and details. The only problem here is processing time - larger sites require longer times to be processed.

3.1.2 Area observation and simulation: RFC

Another method is Random Forest Classifier. There can a lot of different disasters happen in the world, and some of them, like tsunamis, are featuring floods. SfM is not able to get information about surface underwater, as it is almost invisible for it. But RFC is. It uses a set of Red Green Blue (RGB) images with texture information to map an area underwater. Such map can be used for analysis of unreachable places on a site. The test was conducted by Feng et al. 2015 in Yuhao city, China, there the accuracy of the method found was around 87.3% comparing to mapping. Therefore, this method is useful for various SAR operations sites, providing an accurate and convenient mapping. However, the time needed to finish the process is far longer than SfM, so SAR managers must be careful while using this technology (Hailong. 2023).

3.1.3 Structural damage analysis: SURF

Area examination in urban and industrial areas also requires building quality analysis in order to decrease the risks of collapse during operation. SfM can be used to estimate structure state the same way it's used in area examination. The big disadvantage here is the need of full data to be acquired, for example not only the external space, but also the inner. However, there is also a SURF method, which overcomes this issue quite well. It is used to create full detailed images of damaged structures from the outside. The images are then processed by using Mask-R-CNN-based deep learning (R is region), as using Convolutional Neural Networks (CNN) enables to differentiate between the already collapsed objects and not yet destroyed ones. Identified coordinates of defects are next processed by Building Information Modeling (BIM) models, resulting into approximate collapse predictions. The experiment in old Beichuan town, China, confirmed this method to be reliable enough - almost 90% accuracy of the results (Hailong. 2023). That approach helps to avoid extra casualties for both victims and rescue teams during the operation at a cost of time, hence using that method in difficult scenarios (big buildings, complex structures) will definitely improve the overall performance.

3.1.4 Target localization: ABT-YOLOv7 (modified You Only Look Once detection algorithm).

Another objective of site analysis is target localization. Target localization includes searching for people, detecting spots of interest (for example places there people might be under debris, etc) and other important locations. Usually there are several difficulties to perform such with UAVs - bad light conditions, weather, quality of images or video streams, environment and more. Basically, You Only Look Once algorithm (YOLO) algorithm was used alone to identify these features from the images. But when the site was in bad observation conditions, the methods performance worsened. To improve the situation, the You Only Look Once algorithm integrated with AFPN, BiFormer module and TSCODE (ABT-YOLO) model was introduced in (Zhang et al. 2023). So, the Asymptotic Feature Pyramid Network (AFPN), attention module ”BiFormer” and Task- Specific Context Decoupling (TSCODE) algorithm are integrated into YOLOv7. Briefly, AFPN helps to preserve feature information during processing, BiFormer module optimizes the whole algorithm leaving irrelevant regions out of analysis and, finally, TSCODE increases the detection precision. This modification resulted into overall better target identification by UAVs. Figure 2 represents the findings during maritime SAR operations (Zhang et al. 2023):

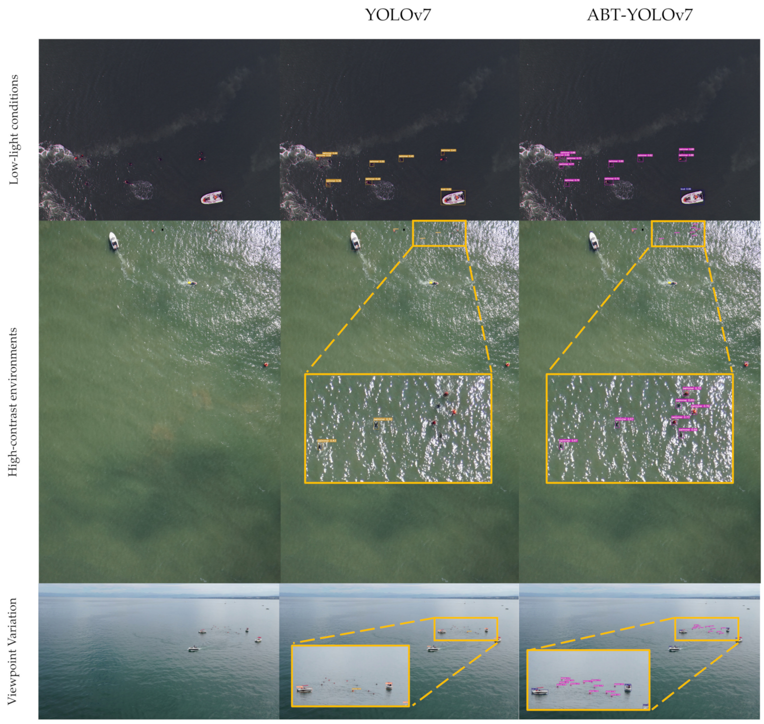

Figure 2: Image of the experiment conducted (Zhang et al. 2023)

Detector	Precision (%)	Recall (%)	mAP (%)	Parameters/M	FPS
Faster RCNN	56.8	43.4	48.5	108	4.3
Cascade R-CNN	87.9	86.3	86.4	68.2	3.7
FCOS	87.4	80.2	85.7	32.1	4.8
YOLOv3	86.1	82.5	85.1	61.5	9.6
YOLOv4	87.6	79.7	84.6	52.5	18.8
YOLOv5	88.7	85.6	86.1	46.2	10.6
YOLOv8	87.0	80.1	84.4	87.6	3.3
ABT-YOLOv7	92.3	91.7	91.6	52.4	7.5

Table 2: Approximate testing results for different methods (Zhang et al. 2023)

Considering the results, using this method in the open areas can enhance the detection of points of interest, leading to faster response of the rescue teams. However, bad weather conditions might dramatically worsen the method's usefulness due to UAV's technical issues.

3.1.5 Target localization: ACA

Targets must be localized as fast as possible, so path planning for UAVs is essential here. One of the methods for effective planning is Ant Colony Algorithm (Wu et al. 2022). The area is taken as a two dimensional surface (as drones fly above on a fixed height) and divided in grids with fixed sizes. Then the application of ACA is similar as to solve Mass Travelling Salesman Problem (MTSP). Hence each node is taken as a ”city”, resulting the whole mesh to be a ”city network”. So each ”ant” (here UAV) is decided the next city to visit by transition rules, travelling through the mesh. The algorithm is run through until the optimal path is found, only then it is ready to use. Optimal path is a path, following which the UAV's devices will cover the whole area of search in the shortest period of time, allowing to conduct fast and effective observation of the SAR operation site.

3.2 Function 2: Interactive - Deliveries and Communication

During the SAR operation, found victims are often in need of different supplies, like water, food, clothes, medicine, maybe some materials, like rope, wood - almost anything. The supply routes are rarely clear on the sites, making it difficult and time consuming to deliver anything. In addition, the team must always act fast and safely. So, UAV's are a possible solution, as in this situation they benefit from their speed, size and the ability to carry few supplies - exactly suitable for water bottles and other light objects. Finally, it might save time and lives, improving the overall performance and making management of SAR events less complicated.

3.2.1 Search and supply: RCT method

So, it is essential to start the treatment of victims as early as possible because it determines the chance of a person to be saved. The article (Veelen et al. 2023) tells about the SAR operations conducted in the mountainous areas in Italy, and states, that one of the biggest issues there is the accessibility to the victims - it takes much time to arrive, however, usually, people can not wait long with heavy injures. So, to improve the situation, authors suggest using UAV's: firstly, manually manipulating the drone with an RGB high-definition camera, scan through the area and find the targets. For instance, the technologies mentioned in 3.1 might be used to plot the map with points of interests. Secondly, then the target is confirmed, the drone is equipped with an emergency kit weighing around half a kilogram:

> “The kit was in a polystyrene box where there were a radio, first aid material (pressure bandages, rescue foil, disinfectant solution), and Personal Protective Equipment (PPE), such as gloves and a filtering facepiece 2 (FFP2) mask (similar to an N95 mask). (Veelen et al. 2023)”

After the drone has reached a target, the package is dropped off as near as possible to the victim. He / she takes it and follows the instructions using a radio to initiate the medical treatment. This technique was tested on a site in Alps by six different teams of four and after compared to the traditional fully manual approach. The results are presented in the figure 3 (Veelen et al. 2023):

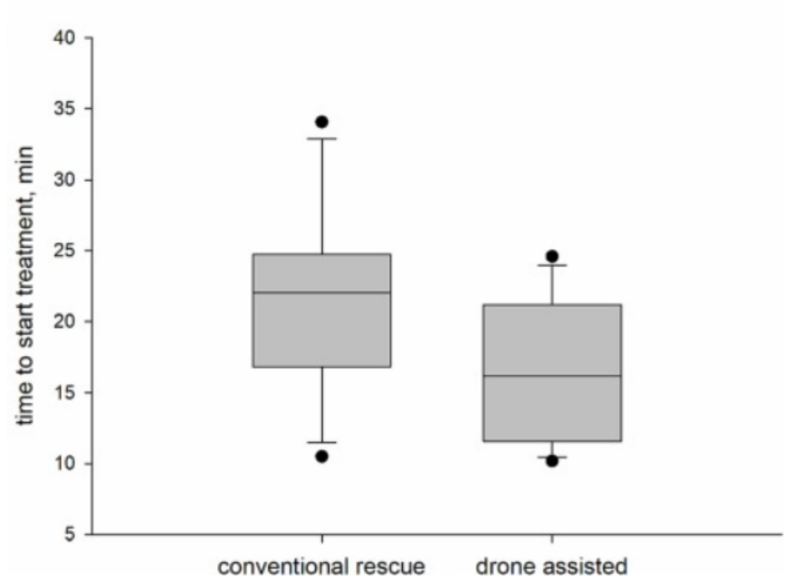

Figure 3: Time results for medical treatment initialisation (Veelen et al. 2023)

The figure 3 shows, that the drone assisted SAR team has fulfilled the task around 6-7 minutes faster comparing to the traditional method. The disadvantages happened are the technical issues - four times out of twenty four tries the drone has failed to transmit image from the camera. But still, UAV’s shown an improvement of overall performance.

3.2.2 Emergency communication: UAV’s Wi-fi network

Emergency situations can happen anywhere. In addition, global warming affects the planet’s climate, as a result causing more catastrophes in the countryside. Forests, mountains, fields, all these areas usually cover to tens or hundreds of kilometers, hence wildfires or similar catastrophes can occasionally put hiking groups, campers or anybody in danger, yet not taking all the wildlife into account. A good communication between the rescue team and the victims is a key to a successful escape. An innovative solution is introduced in Technology Collection journal (Mayor et al. 2019) using a local Wi-fi network instead.

The Wi-fi network demands the device it can be connected to. So, for example a mobile phone, commonly a person has one. He / she connects the device to the local network created by the drone's IEEE 802.11 Access Point (AP) and then uses his / her phone for real-time communication. This way the whole area of point's of interest is covered and therefore provided a connection. On the other hand, despite the great coverage, there is a limit for amount of established accesses. According to the article (Mayor et al. 2019), this amount is specified by several aspects:

1. Speech quality level (SQL) of each connection established must be of at least the minimum value. SQL (R) is established by the equation below (simplest form):

$$R = 94.2 - I_d - I_{e,eff} \tag{3.1}$$

where I_d is the effect due to delay, $I_{e,eff}$ is the affection by low bit-rate coding and packet loss The minimum value is 65.

2. The suggested implementation method of drones must be such, that the power consumption of each UAV is the lowest possible, so the network can be maintained during a sufficient time period. The average Network Interface Controller (NIC) consumes 0.15W for such purposes.

To get the implementation results, the simulation was established according to the conditions presented above. There are 50 victims trapped on $100 * 100$ m^2 area and it is assumed that everyone has a working phone at the moment. The target is to find out the minimum number of AP's needed to connect all the users to the network. Table 3 presents the most optimal solution found in the study:

Drone (i)	x_i	**C(i)**	Algorithm / Simulation	
			$R(i)[1-100]$	$\frac{E(i)}{E_{max}}$
1	(20, 20, 20)	11	86 / 87	0.10 / 0.09
2	(30, 70, 20)	11	85 / 87	0.11 / 0.10
3	(80, 30, 20)	15	80 / 83	0.12 / 0.11
4	(80, 80, 20)	13	83 / 85	0.11 / 0.10

Table 3: Simulation results (Mayor et al. 2019)

where x_i is the drone's position (x, y, height), $C(i)$ is the number of connected users, $R(i)$ is the SQL and $E(i)$ is drone's energy consumption.

So, the Figure 3 shows, that the SQL of the signal provided is still high even with 10-15 connections. Such a good result might be caused by the suitable area with appropriate grouping of people, as these are the leading factors. Also, with uniform sparsity, each drone helps the other by sharing the users together. However, victims rarely happen to be located this way.

To evaluate the performance of the method in different situations, additional tests with low and high sparsity were conducted and the results summarized in the figure 4 (Mayor et al. 2019):

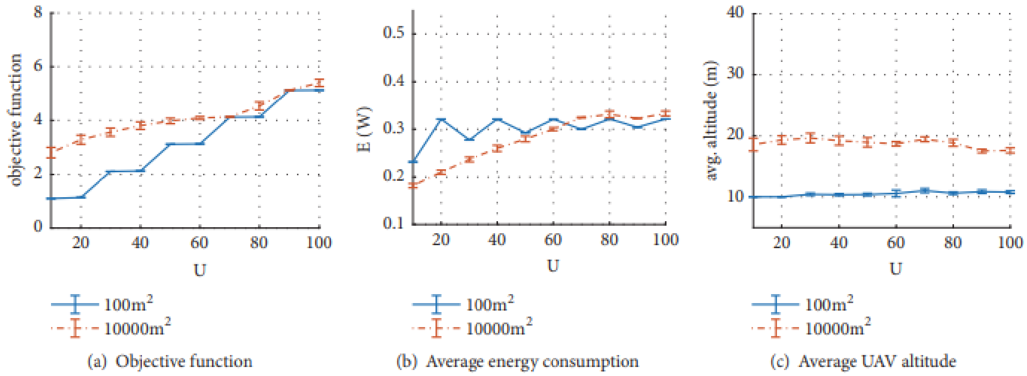

Figure 4: Results of additional tests

where *objective function* is the amount of deployed drones, U - number of victims, E - average energy consumption of connected users in watts and *avg. altitude* is the average altitude of a drone sharing the signal.

As a result, the method shows, that efficient solutions are available in various cases. However, in the case of high density, the amount of drones increases gradually with approximately each 20 users more, comparing to smoother slope in low density case. That happens due to the dramatic decrease in SQL, which must be held above the minimum.

All in all, this method can be used in SAR operations of different type to provide reliable communication between the SAR team and the victims in absolutely different situations. But, three main issues exist: weather conditions, battery life and availability of mobile devices. These must be always considered when using this technology.

3.2.3 Emergency communication: WRN

Despite the open areas, disasters happen in urban areas too, and, unfortunately, quite often. Whereas open areas trap people around, in the industrial / city areas victims are usually underground or under the debris. These have many metallic substances inside, causing the electromagnetic waves to be absorbed and become weak on the way to the receiving device. However, there is an approach - (Vo and Hoang 2020) introduces the use of UAV's as transmitting nodes for signal navigation.

Unlike the direct communication, this method is based on Multi-hop Mobile Ad-hoc Network (MANET) technology, which is often used in emergency communications, as it is independent, dynamic and does not utilize any complex infrastructure. So, each drone is used as a relay node, providing connection between the separated transmitter and receiver points. That adds mobility and additional radio propagation coverage to the system. Each drone uses a distributed Space-Time Block Code (STBC) encoding scheme, allowing to reach high speeds and accuracy of transmission without complex coding techniques. The figure of the whole network is presented below:

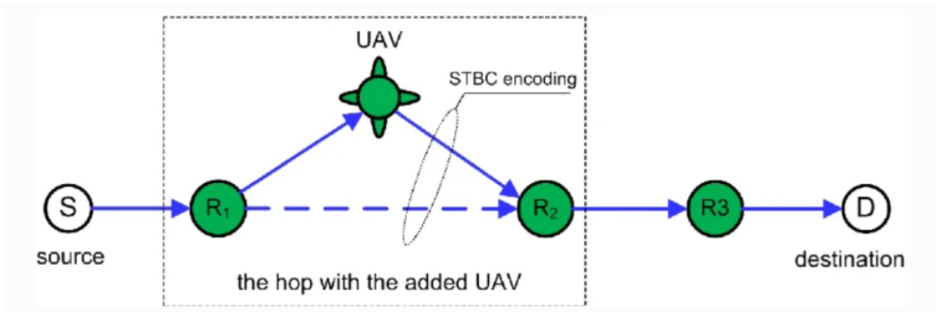

Figure 5: Connection scheme of WRN

The same way the whole system is constructed, adding more hops between the nodes. However, the modelling and estimation of all UAV's positions would take a lot of time, hence not meeting the SAR operation requirements. In order to overcome this issue, the network's parameters are derived from the equivalent single UAV hop, dramatically reducing calculation times, keeping the quality of the results on a high level and allowing to estimate the connection's reliability. That approach was used in a simulation, which examined the WRN of a transmitter and receiver separated on 300 metres from each other. Initially noise level at the receiver is -85 dBm and UAV's transmission power is 15 dBm. The results are presented in the figure 6.

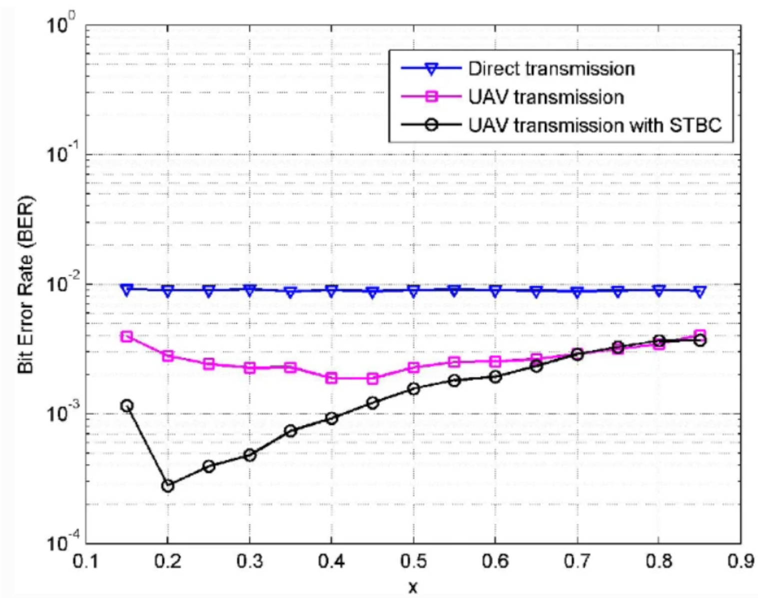

Figure 6: Simulation results of WRN

According to the graph, it is clearly seen, that the Bit Error Rate (BER) of direct transmission is high, staying at 10^{-2}. However, the introduction of UAV between the nodes enhances the performance as it brings additional transmitting power, reaching minimum BER value (x = 0.45) in the coverage area of both nodes (x is a relative distance, there 0.9 = 90% of 300 metres). However, the situation changes with installation of STBC encoding, greatly decreasing the BER with it's minimum at position x = 0.2. This is caused by the cooperative diversity gain, which is obtained by simultaneous transmission of the signal from both UAV and transmitter. That system can also be improved by combining the signals: firstly, a signal is sent by the transmitter and kept at the receiver; secondly, the signal from both UAV and transmitter is sent and then all three are combined together, resulting in a better performance. All in all, despite it has the same disadvantages as the method described in section 3.2.2, it can make the communication establishment during the SAR operation much easier in spite of almost any circumstances (Vo and Hoang 2020).

3.3 Conclusion

There are many advantages to implement UAVs in SAR operations. It makes the operation to consist less of routine jobs, like observation, estimation, continuous supervision, supply, communication establishment and others, allowing to focus on more important problems. It also introduces new approaches in target detection and communication fields. All these result into better efficiency of rescue teams, less casualties and overall performance improvement. In addition, UAVs are not always fixed to their jobs, so the whole system can dynamically adapt to the ongoing changes on the SAR site. But, there is nothing ideal, and each of these methods have their own disadvantages. Common issues are energy utilization and technical issues due to weather conditions, but there is also an essential one - type and model of a UAV used. That defines the capabilities of the drone, resulting into direct affection of method's efficiency and outcomes.

All in all, rescue departments should start using UAV technologies in SAR operations, as these allow to save more people and lower risks during the process. However, SAR operation managers must always take into account all the issues connected to these approaches - incorrect usage will waste time and may cause worse results.

4 Present UAV models used in SAR operations

Here the different models of UAVs used in SAR operations are presented. The chapter contains the review of each model type - main use and on-site performance as well as the short description of their structure and capabilities.

4.1 Purpose of UAV model variety

To begin with, there are a lot of different UAV models present on the market, but two main types - Fixed wing UAVs and Rotary UAVs, and there is a reason for that. Taking all the approaches considered in chapter 3 into account, it can be easily noticed, that each of these need different characteristics present in the drone. For example, target localization and area examination algorithms could better be done by high speed UAVs. Sometimes areas might be huge, but SAR operation should better not last long. Another case - communication establishment. Here the drones with good balance and dynamics are the most preferable, as they can change and fix their position fast on a response. Hence, it is essential to use appropriate models for particular approach. Otherwise the results will be worsened.

4.2 FwUAV

Fixed wing UAVs are similar to the piloted planes. They have wings, which lift up the vehicle using the incoming air flow. The machine is kept in movement by jet engines, combustion or electric powered propellers, etc., which keep the forward velocity at the desired value (Bashyam and Guggenheim 2019). Fixed wing UAV's are being controlled through roll, pitch and yaw orientation angles. Changing these using special rudders installed in different places on the hull allows the remote operator or embedded system to maneuver the drone and control it's speed. Below is the picture of a FwUAV model:

Figure 7: Example of a Fixed wing UAV type (Hailong. 2023)

This kind of structure brings several advantages to the vehicle. Firstly, FwUAVs consume less power to fly than any other UAV type. This is because they are designed with high glide ratio, leading to production of weak forces, finally resulting into low power consumption. Secondly, such economy of the battery charge or fuel enables the drone to use that resource for other purposes - for example, better hardware can be installed on the UAV, therefore improving the quality of collected information. In addition, such design can withstand high loads during the flight, hence more weight can be put on it. That opens many new opportunities to upgrade the drone for specific operations.

On the other hand, some drawbacks appear. One of these - it is poorly controllable. In order to turn to the sides or go up / down, these planes need to fly through some distance first, they cannot simply rotate around their center of mass to change direction. Therefore, the operator must estimate the trajectory beforehand, however it might not be obvious sometimes. The other issue is constant movement. In case of area exploration, fixed wing cannot stop in place to examine the area more carefully due to constant forward velocity condition. All in all, this type of UAVs is the best candidate for large area explorations in short-medium time periods.

4.3 Rotary UAV

Rotary UAVs are using same principle as common helicopters. While the design of these can vary depending on the case, the mechanism of flying is similar. These UAVs use lifting force produced by the rotating propellers, which are directed to the top, usually perpendicularly to the ground. This force allows them to float in the sky in any direction (Bashyam and Guggenheim 2019).

4.3.1 hUAV

So, as the name states itself, this type of UAV is basically a remote-controlled helicopter. It has a main propeller, which is installed on the top of the fuselage, and a small one in it's tail. The main lifts up the vehicle, while the secondary balances the torque of the main motor (Hailong. 2023).

The orientation approach is same to Fixed wing UAV - roll, pitch and yaw. In contrast to the previous type, the control of these angles is achieved through changing the pitch of both propellers. These changes adjust the created collective thrust in the needed direction, which defines the helicopter's orientation in space. In order for helicopter to fly smoothly, the engine's torque and speed values are continuously set to the needed levels until landing (Watkinson 2004). The common vehicle looks like in the figure 8:

Figure 8: Example of a Helicopter UAV type (*AeroExpo* 2024a)

The design of a helicopter is a difficult process, because it involves a set of complex differential state equations to be computed, many estimations, controllability and stability problems and others. However, despite these issues, this type of structure brings a huge advantage to the vehicle - agility. Helicopter UAVs are quite fast and able to perform quick maneuvers, which make them a perfect choice for fast operation in complex environments. In addition, hUAVs can stay in place hovering in the air, which also expands their implementation possibilities (Bashyam and Guggenheim 2019).

But, a complex structure results in a big trouble in a case of maintenance. As mentioned just above, not only the structure is difficult, but also the rotors are of specific design, including, for example, multiple steering gears and other expensive, hard-to-manufacture compounds. These dramatically increase the maintenance costs, as well as maintenance difficulty. Hence, taking everything into consideration, it can be surely said, that these UAV's have a great potential in different kinds of observation tasks.

4.3.2 MrUAV

Similar to helicopter UAVs, Multirotor UAVs are of Rotary type. These also use the lifting force created by rotating propellers but the implementation is different. In contrast of using one big drive, MrUAVs are equipped with multiple rotors, usually at least with four located uniformly throughout the whole structure.

The propellers must be put in pairs in order to cancel the torque they create. The cancellation mechanism is simple - these rotors just rotate in opposite direction to each other. This way all the rotors themselves cancel any additional translation and rotation (except vibration) of the drone, leading to systems controllability. MrUAV is controlled using the same angular definitions as hUAV and FwUAV. In order to maneuver, the differential thrust system is used (Hailong. 2023), which works the way described below:

> "...the pitch and roll movements are controlled by the differential thrust between front–behind pairs of rotors and left–right pairs of rotors, separately. The yaw movement is controlled by the differential thrust between diagonal pairs of rotors, generating horizontal torque clockwise or counterclockwise. (Hailong. 2023)"

The common Multirotor UAV model is presented in figure 9:

Figure 9: Example of a Multirotor UAV type (*AeroExpo* 2024b)

Continuing the topic, that type has pretty similar advantages to hUAV. But there are some differences. One of them is the structure simplicity. MrUAV is easy to design and manufacture, which leads to cheaper maintenance and cost itself. Another thing is the improved stability. MrUAVs are far stabler than hUAVs due to more precise control of each motor. Moreover, MrUAV might transport heavier supplies to remote places. However it's payload is lower than of FwUAV. High power consumption is also common for Rotary UAVs. In conclusion, this drone might be utilized for communication establishment and emergency supply. It is not a good variant to use it as an observation machine, but can be efficient in small areas or hard environments like ruins or thick woods.

4.4 HyUAV

The last type is Hybrid UAV. It is usually considered as the mixture of Rotary and Fixed wing UAV technology. In other cases it might also mean the energy it uses - petrol & electricity, gas & electricity, etc. This section is about the first definition. So, the working mechanisms of separate approaches were explained above. Now, the mixture is introduced. HyUAV commonly consist of one or several wings and pairs of horizontal propellers. There are three common structuring methods, which define the flight modes and vehicle characteristics (Gu et al. 2017).

4.4.1 Tail-sitter VTOL UAV

So, first is a Tail-sitter VTOL UAV. It has a hull similar to FwUAV and a pair of propellers fixed on it's wings. It's tail is designed to support the drone to stand in vertical position. So, due to this approach this UAV starts take-off from lifting the whole structure to some height and then, using it's rudders, tilts itself horizontally to continue flight. It has a known issue - poor controllability. They are easy to produce and repair, but are very complex in design because of stability tuning, hence making a target of hovering or dynamic place changing more difficult. Their operation is worsen in bad weather, especially additional winds (*Tail-sitter VTOL | PX4 User Guide (main)* 2024). All these descriptions lead to a good use of this model in big scale objectives, like vast area observation and supply, etc. The example of a Tail-sitter model is presented in figure 10:

Figure 10: Example of a Tail-sitter VTOL UAV type (*Tailsitter VTOL | PX4 User Guide (main)* 2024)

4.4.2 Tilt-rotor VTOL UAV

Next, the Tilt-rotor VTOL UAV. As the name states itself, this aircraft works due to direct speed and orientation control of it's rotors. Usually these have wings and a pair of propellers, connected via rotational joints on the ends. So, for take-off and landing operations, these drones keep rotors in vertical position, for flight - they change to horizontal. Rotational speed of motors is controlled continuously. There are two main problems in this model. It is hard to design such an aircraft with freely controllable rotors because of structure's and inner system's complexity. The other source is the result of the first - weight. These make this type a universal vehicle for SAR operations, as they present a ”transition state” model between the Fixed-wing and Rotary types (*Tilt-Rotor Drones | Tilt-Wing UAV* 2024). They are also capable of carrying various equipment and have enough battery life. A common tilt-rotor type model is shown in the figure 11:

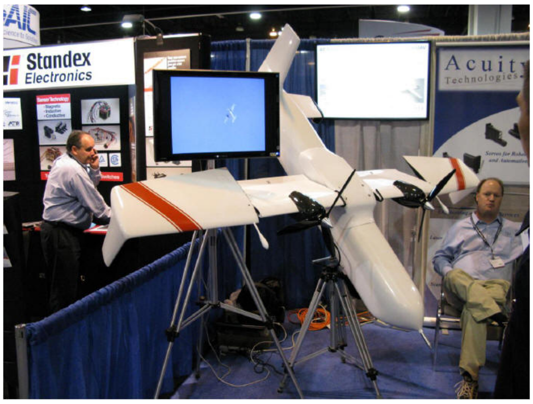

Figure 11: Example of a Tilt-rotor VTOL UAV type (*Tilt wing unmanned aircraft* 2024)

4.4.3 Dual-system VTOL UAV

The last is the Dual-system VTOL UAV, which is also presented in the figure before 12. Here two propulsion systems are included. One of them is two pairs of vertical propellers for lifting similar to MrUAV. The second is a horizontal thruster, that keeps running during level flights. The control of the aircraft is achieved by manipulating the rudders, which are located on wings and tail. All parts are easy to design and manufacture, as the whole assembly is rigid except the ailerons. However, the development of the software part is a challenging task. Another two general drawbacks are the additional wind resistance and extra weight. Considering all the aspects, this drone can be best implemented for emergency communication purposes, as it can reach distant places at less energy consumption rates, as well as hover in place. It's VTOL ability is also very beneficial for such objectives (Hailong. 2023). Common Dual-system VTOL UAV looks like on the figure 12:

Figure 12: Example of a Dual-system UAV type (*SkyEye - ElevonX | Professional UAV solutions* 2020)

5 Discussion and the future of UAVs in SAR operations

This chapter discusses the findings and results of the research conducted.

5.1 Discussion

With the technologies introduced in the previous chapters, it is now important to consider them more thoroughly. The methodologies above prove that UAVs might potentially become an essential tool in any SAR operation for localization, observation, communication and supply purposes. The tests performed also confirmed a successful implementation of drones, and there are several reasons.

To begin with, all drones are equipped with various sensors, which allow them to process the site accurately. They also enable the machines to overcome different obstacles, like walls, soil, water - almost anything. Module configuration also gives an opportunity to work during bad weather conditions, like thick fog and heavy rain. And here is one of the major advantages of UAVs over manual labour - the information flow from all of the sources is huge, and, if people need time and experience to prepare themselves for such work, artificial intelligence or embedded systems become able to manage the data flows with a very high speed after spending far less time on training. In addition, machines do not experience stress, and hence their own working efficiency does not change during operation, but it drops through years of duties because of natural phenomenon, like component degradation, parts erosion, circuit outage and so on. Processing rates might also be the main reason for the UAV technology being researched and developed more in site analysis and communication domain than in physical UAV manipulators. Due to this potential, the ongoing UAV development is more focused in networks, software and hardware of sensors. Furthermore, these are easier and cheaper to establish and test than the motors for higher supply capabilities. Also the supply drone is expensive and heavy comparing to of site analysis type, and hence the latter is more convenient to implement in SAR operation, but, despite these factors, the research is ongoing in both domains.

UAVs are a universal tool for a big variety of jobs, but, on the other hand, the limitations still apply to their usage. One of the issues is battery life of a machine. Every time the drones are sent to do their jobs, the related supervisors must always track the charge level of each device, so the SAR operation manager can optimize the UAV usage. Nowadays the development of long-lasting charge accumulators is ongoing. That might expand the capabilities of UAVs during SAR operations, which sometimes might demand the devices to work continuously for days. In addition, weather conditions are vital in UAV deployment, because, for example, their motors are not capable to cope with harsh winds, hence the flight might immediately, or in short time period, cause high damage to the general parts and inner systems, which may wear the equipment out faster. Not the last, but important thing - at the moment, the level of cross-communication between drones is quite low and that demands the UAV supervisor to control the situation, hence leading to a new type of job in SAR departments, which must be first studied in terms of education, standards and work optimization, and only then applied.

Both approaches - manual and automatized - have their own pros and cons, and, as the chapters above describe, the mixture of both leads to an absolute new level of SAR operation efficiency and to appearance of a complete new field in SAR to study and work on. Rescue teams and drones working together dramatically improve the results and efficiency of the operations. The result is due to the teams became more informed and made better decisions, as well as UAVs were able to supply the rescue teams with data and other tools dynamically following their needs. Hence, while the machine's self-governing is still poor, the personnel can take the role of the processed data and decisions manager, as well as drones can benefit to information mining abilities of humans. There is also a huge question exists about regulatory and ethical issues around UAVs. The problem is connected to many yet unresolved issues and paradoxes of philosophy, law, privacy and morale, hence the integration of UAV-supported working principles in SAR would be the most relevant solution for future development.

6 CONCLUSIONS

In conclusion, this thesis has reviewed the usage of UAVs in SAR operations. Through the comprehensive literature study, the key trends of UAV technology development and usage approaches were identified. The research result indicates, that UAVs can be successfully integrated in the operation process for automation of certain routines, but the capabilities of managers and machines introduce different challenges for such implementations.

Considering the empirical evidence, the paper underscores the positive effect of UAVs integration on the operation results, improving the survival chances of rescue team members, as well as increasing the number of successful findings. But it also draws attention to the importance of the correct task allocation for the drones and optimized dynamical management.

Continuing the topic, the study introduces the general UAV models, adding up to the width of their application range. In addition, it reminds how essential is it to consider the limitations of available tools during planning. However, it also brings a new outcome - the collaboration of drones and rescue teams on the sites is the future of SAR operations. Summarizing the existing and developing UAV technologies, the thesis only contributes to the ongoing research. Furthermore, it sets the stage for the absolutely new branch of SAR operations - UAV-supported rescue teams and their working principles.

All in all, the integration of new technologies in our life can significantly benefit the humanity, bringing automation and the ability to focus on more vital issues, leading to the improvement of overall results. But, based on the example of UAV usage in SAR operations, it is still in the early stages, and hence needs time and attention to unlock its full potential. By addressing the introduced challenges and exploring the new, we can use the full power of these technologies to develop even more effective methods to conduct SAR operations, contributing to the current and future generations.

REFERENCES

AeroExpo (2024a). en. URL: https://www.aeroexpo.online/prod/alpha-unmanned-systems/product-175258-29476.html (visited on 01/05/2024).

AeroExpo (2024b). en. URL: https://www.aeroexpo.online/prod/up-caeli-via-srl/product-186859-67199.html (visited on 01/10/2024).

Bashyam, Ashvin and Jacob Guggenheim (Apr. 2019). "UAVs for Wilderness Search and Rescue: Real-World Considerations and Technology Roadmap for Fixed Wing UAVs". en. In: *JSAR* 3.1. ISSN: 22305734, 22305734. DOI: 10.61618/GLOX4896. URL: https://journalofsar.com/uavs-for-wilderness-search-and-rescue-real-world-considerations-and-technology-roadmap-for-fixed-wing-uavs/ (visited on 12/30/2023).

Comission, Europian (2023). "search and rescue (SAR) operation - European Commission". en. In: (). URL: https://home-affairs.ec.europa.eu/networks/european-migration-network-emn/emn-asylum-and-migration-glossary/glossary/search-and-rescue-sar-operation_en (visited on 12/23/2023).

Feng, Quanlong, Jiantao Liu, and Jianhua Gong (Apr. 2015). "Urban Flood Mapping Based on Unmanned Aerial Vehicle Remote Sensing and Random Forest Classifier—A Case of Yuyao, China". en. In: *Water* 7.4. Number: 4 Publisher: Multidisciplinary Digital Publishing Institute, pp. 1437–1455. ISSN: 2073-4441. DOI: 10.3390/w7041437. URL: https://www.mdpi.com/2073-4441/7/4/1437 (visited on 02/15/2024).

Gu, Haowei et al. (June 2017). "Development and Experimental Verification of a Hybrid Vertical Take-Off and Landing (VTOL) Unmanned Aerial Vehicle(UAV)". In: DOI: 10.1109/ICUAS.2017.7991420.

Hailong., Lyu Mingyang; Zhao Yibo; Huang Chao; Huang (2023). "Unmanned Aerial Vehicles for Search and Rescue: A Survey". English. In: p. 3266. DOI: 10.3390/rs15133266. URL: https://www.proquest.com/docview/2836484671?forcedol=true&parentSessionId=4oiMNZppMlY9WB3MCVmN1n40VWDdV8qpu5VK%2FWm4P00%3D&pq-origsite=primo&sourcetype=Scholarly%20Journals&forcedol=true (visited on 12/20/2023).

Mayor, Vicente et al. (2019). "Deploying a Reliable UAV-Aided Communication Service in Disaster Areas". eng. In: *Wireless communications and mobile computing* 2019, pp. 1–20. ISSN: 1530-8669.

Organization, International Maritime, ed. (2006). *IAMSAR manual: international aeronautical and maritime search and rescue manual*. en. 5th ed. London : Montreal, Quebec: IMO ;

International Civil Aviation Organization. ISBN: 978-92-9194-796-6 978-92-9194-816-1 978-92-9194-790-4.

Piatt, Lance (2023). “5 Common Challenges Facing any Search and Rescue Team | Rigging Lab Academy”. In: (). URL: https://rigginglabacademy.com/the-5-common-challenges-facing-any-search-and-rescue-team/ (visited on 12/23/2023).

SkyEye - ElevonX | Professional UAV solutions (Apr. 2020). en-GB. URL: https://www.elevonx.com/solutions/skyeye/ (visited on 01/11/2024).

Tailsitter VTOL | PX4 User Guide (main) (2024). URL: https://docs.px4.io/main/en/frames_vtol/tailsitter.html (visited on 01/11/2024).

Tilt wing unmanned aircraft (2024). URL: https://barnardmicrosystems.com/UAV/milestones/tilt_wing.html (visited on 01/11/2024).

Tilt-Rotor Drones | Tilt-Wing UAV (2024). en-US. URL: https://www.unmannedsystemstechnology.com/expo/tilt-rotor-drones/ (visited on 01/11/2024).

Tipton, Michael et al. (2022). “Survival time and search time in water: Past, present and future”. eng. In: *Journal of thermal biology* 110, pp. 103349–. ISSN: 0306-4565.

Veelen, Michiel Jan van et al. (2023). “Drones reduce the treatment-free interval in search and rescue operations with telemedical support – A randomized controlled trial”. eng. In: *The American journal of emergency medicine* 66, pp. 40–44. ISSN: 0735-6757.

Vo, Nguyen-Son and Van-Phuc Hoang (2020). “An UAV and Distributed STBC for Wireless Relay Networks in Search and Rescue Operations”. eng. In: *INISCOM*. Vol. 334. Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering. Switzerland: Springer International Publishing AG, pp. 57–73. ISBN: 303063082X.

Watkinson, John (2004). *Art of the helicopter*. eng. Oxford ; Elsevier Butterworth-Heinemann. ISBN: 1-280-96648-3.

Wu, Meiping et al. (2022). “MTSP-ACA for Multi-UAV Path Planning Applied in SAR Operations in Mountainous Terrain”. eng. In: *Proceedings of 2021 International Conference on Autonomous Unmanned Systems (ICAUS 2021)*. Vol. 861. Lecture Notes in Electrical Engineering. Singapore: Springer Singapore Pte. Limited, pp. 3260–3268. ISBN: 9811694915.

Zhang, Yijian, Yong Yin, and Zeyuan Shao (2023). “An Enhanced Target Detection Algorithm for Maritime Search and Rescue Based on Aerial Images”. eng. In: *Remote sensing (Basel, Switzerland)* 15.19, pp. 4818–. ISSN: 2072-4292.