Simulating and Evaluating Search Strategies for Highly Accurate Localization based on Wireless Technologies using Autonomous Unmanned Aerial Vehicles*

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Abstract. When persons are reported missing, the authorities are under severe time pressure to localize and safeguard them. This is especially the case, if the missing persons' lives might be threatened, e.g. if the night approaches and the outside temperatures are endangering survival over night. However, the localization of the missing persons can be quite challenging in many scenarios such as rough terrain where ground units of the authorities have limited access. In this paper, we therefore present a new approach with four different strategies for automated Search-And-Rescue (SAR) missions, i.e. the localization of missing persons' mobile devices using unmanned aerial vehicles. The strategies are compatible with multiple wireless technologies, e.g. cellular networks or WiFi. They are then evaluated with extensive simulations to cover a wide range of possible scenarios, including different search area shapes and sizes, missing persons' velocities, and equipment characteristics. The evaluation focuses on the required time to localize the device, the success rate of the SAR mission, and the running costs of the mission. Our results show that the missing person can be found quickly, within 20 to 30 minutes in most scenarios. For slow-moving persons, the time of localization could even be significantly reduced. Finally, we provide an overview of the advantages and disadvantages of each strategy. This allows to select the best one for a given scenario.

Keywords: Localization · Unmanned aerial vehicles · Search and Rescue · Wireless technologies.

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1 Introduction

Every day, there are between 200 and 300 new cases of missing persons registered in Germany [12] and even more in the USA (around 1500 per day in 2022) [9]. Once a missing person is reported and if their life is assumed to be in danger or the person is a child, the authorities initiate a Search-And-Rescue (SAR) operation [12]. Especially if the missing person might be injured, e.g. if a hiker went missing or if the missing person is known to be suicidal, the authorities are under significant time pressure to find them. If necessary, they use thermal cameras, SAR dogs or helicopters in order to increase their chances of quickly finding the missing person [12]. Another tool which is available to the authorities in such an operation is the localization of the missing person's technical devices, such as mobile phones or wearables. The SAR mission can become increasingly difficult in mountainous terrain or in other regions that are hard to reach and search. The operational units need to drive around in cars or carry their technical equipment by foot when trying to locate a device, which can turn out to be inefficient and slow. Such a SAR mission can require a significant number of personnel and technical resources and become rather costly. According to a study by Röper et al. from 2020, operating a helicopter in an emergency services scenario can cost 70 euros per minute [23].

To address these issues, several papers in the literature examine the search for a person using drones in various ways. Exemplary, the authors in [15] introduce a probabilistic search approach where several drones are cooperating. In terms of technology, some of the work focuses on locating the mobile device of the missing person in a cellular approach with machine learning [1]. Others use different technologies such as optical approaches using cameras on the drones [24]. However, the approaches to locate the mobile device of a missing person are complex and computationally intensive. To perform the computations, either more equipment needs to be mounted on the drones or the information has to be transmitted to a centralized computation unit. SARDO, e.g., uses an Intel NUC board mounted on the drone to execute a convolutional neural network and find the future user trajectory [1,16].

Thus, in this paper, we introduce a new and less computationally intensive search approach to support the authorities in finding missing persons. The basic idea is to send out drones, equipped for device localization, to autonomously search for the missing person's mobile device. Since drones are not limited to streets and paths on the ground, they can search areas more efficiently and find the missing person, in the following also referred to as the target, faster than operational units on the ground, while on the other hand, they are limited in flight time and supported payload. The search pattern of the drones is determined by one of four search strategies. They consist of multiple steps that gradually delimit the area of possible target positions before estimating the final position more precisely. The operational units would then be able to look for the missing person through other approaches, e.g. with SAR dogs, at the same time.

These four strategies are then evaluated with extensive simulations to cover a wide range of possible scenarios. In particular, we consider different search area shapes and sizes, different target velocities, and characteristics of the equipment used. As mentioned before, the time to find a person is of utmost importance for the authorities to increase the chances of survival. Thus, the finding time is a key aspect of our results for each strategy. In addition, we analyze the costs and the success rate of a SAR mission. The main message of this paper is that the most suited strategy for a SAR mission with drones depends on the individual scenario. In particular, this paper contributes the following:

- We introduce the novel idea of end-to-end automation of SAR missions and design UAV-based approaches specifically fulfilling the requirements to achieve this high level of automation.
- We introduce four novel multi-stage search strategies using drones to localize the mobile device position of a missing person.
- We evaluate each of these strategies with extensive simulations in various scenarios. Based on these results, we compare the strategies and identify the most suited one for a certain scenario.
- We developed a framework to easily implement, evaluate and optimize further search strategies that are suited to more specific scenarios or operational needs.

The collection of location information can be seen as an invasion of privacy. However, our clear objective is to facilitate SAR missions and the strategies provided in this paper are only intended to be used by authorities that are looking for missing persons.

The remainder of the paper is structured as follows. In Section 2, background on technical aspects of locating devices for various technologies is given, followed by a discussion of related literature. Section 3 presents the four search strategies and explains them in detail. These strategies are then evaluated with simulations in Section 4. Finally, Section 5 concludes the paper.

2 Background and Related Work

The terms localization and positioning both refer to the estimation of the location or position of a target device, which has a transmitter and a receiver [7]. In this paper, the terms location and position are used synonymously, and the target, which is to be localized, is the device of a missing person.

The mobile stations used to find the position of the target are called reference stations. In this work, they are equipped with a transmitter and receiver [7] and mounted on unmanned aerial vehicles (UAVs). If there is no obstacle between the target and a reference station, they are in Line-Of-Sight (LOS). The quality of the location estimation can depend strongly on the LOS conditions and is best when there are no obstacles between the stations [20].

2.1 Proximity-Based Localization

The proximity-based localization is the simplest, but also the most inaccurate localization technique. For mobile networks, it is also called the cell identity

(CID) technique, since for this method, the CID of the serving base station of the missing user equipment (UE) is provided [20]. With the CID, the service provider also transfers the location of the base station and the approximate area of its cell [5]. The localization result is then as accurate as the size of the cell, but it can be used as a first step in a localization process to limit the search area for further, more precise techniques. If the UE has previously lost the connection to the base station, the last cell it was using can be transmitted instead, which might further decrease the accuracy of this technique. For other technologies such as Bluetooth beacons or Wi-Fi networks, their respective serving area could be considered, but in theory these will be quite limited compared to cellular systems.

2.2 Multilateration

Multilateration is a range-based positioning technique, which uses the distances between the target and multiple reference stations to estimate the position of the target. For multilateration in a 2D space, at least three reference stations are necessary (trilateration). In three dimensions, there is a need for an additional reference station [7].

Three different metrics can be used to estimate the distances between the target and the reference stations: Received Signal Strength (RSS), Time of Arrival (ToA), and Time Difference of Arrival (TDoA) [31]. The following subsections describe RSS and ToA. With these metrics, a synchronization between the reference stations and the target is necessary. In this work, we assume to have this synchronization.

Received Signal Strength The RSS indicates the signal strength of the incoming radio signal at a reference station on a logarithmic scale. The power balance Equation 1 shows how the signal attenuation between the target and the reference station can be calculated from the RSS [7]:

$$\begin{aligned} RSS_i(dBm) =& P_{t,i}(dBm) - L_{t,i}(dB) + G_{t,\theta,\phi,i}(dB) - L_{p,i}(dB) \\ &+ G_{r,(\theta\pm\pi),(\phi\pm\pi),i}(dB) - L_{r,i}(dB). \end{aligned} \tag{1}$$

The index i stands for the ith reference station. $P_{t,i}$ is the transmitting power at the ith reference station. $L_{t,i}$ and $L_{r,i}$ denote the losses at the transmitter and receiver. $G_{t,\theta,\phi,i}$ and $G_{r,(\theta\pm\pi),(\phi\pm\pi),i}$ are the transmitting and receiving antenna gains. They depend on the radiation pattern and the direction of the antennas, where θ is the horizontal angle and ϕ is the vertical angle. The propagation loss $L_{p,i}$ is distance-dependent and can therefore be used to estimate the distance between the target and the ith reference station [7].

Time of Arrival To estimate the distance via the ToA, the propagation speed of the radio wave is multiplied with the signal travel time [31]:

$$\hat{d}_i = c(\hat{\tau}_{ToA,i} - \tau_{ToT,i}) \tag{2}$$

where ToT stands for the Time of Transmission, the index i denotes the ith reference station, and c is the speed of propagation which can be assumed to be the speed of light in free space ($c = 2.99792458 \cdot 10^8$ m/s) [7]. $\hat{\tau}_{ToA,i}$ is the estimated ToA at reference station i.

2.3 Positioning and Localization for Devices

Locating a missing person via their mobile device is prone to the risk that they might not be carrying one. However, the omnipresence of mobile devices justifies the assumption that the missing person is carrying some kind of mobile device. Generally there are two options to estimate the position of a device as a third party. If the device cooperates, the third party can leverage existing positioning services such as GPS or vendor specific frameworks such as Google Play Services, which greatly improves the accuracy. Mobile networks, such as LTE or 5G, also provide specific protocols, i.e. the LTE Positioning Protocol (LPP), for the network operators to use device-assisted positioning methods. This is referred to as positioning.

If the device is unable to locate itself, or non-cooperative (e.g. because the third party is not the network operator), this is referred to as localization and other means are required to estimate the position. Especially smaller devices, such as Bluetooth or LoRaWan beacons do not offer device assisted positioning protocols and often have no way to measure their own position. In our scenario, we assume this case, where we need to rely on measurements performed by the authorities themselves, such as RSS and ToA measurements. This requires the availability of a persistent identifier in the radio communication, so that multiple measurements can be attributed to the correct devices.

An additional problem is to predict the frequency the target device uses. In mobile networks, this is based on the current or previous cell, which limits the options but still requires probing of different possibilities. For this reason, we propose a two-stage protocol with a larger first drone, that is able to carry multiple transceivers to parallelize the search and smaller drones that can be used once the target frequency is known. We call this larger drone 'Catcher', as its primary task is to catch the device's signal and share the information with the other drones. These smaller ones only need a single transceiver and can therefore significantly reduce the required payload and thus, increase the maximal flight time and reduce the cost.

In the following sections, some of the most prevalent radio technologies are presented and their suitability for our localization approach is discussed.

Cellular Cellular technologies, such as GSM (2G), LTE (4G) and NR (5G) have seen widespread adoption, reaching about 6.4 billion subscriptions worldwide in 2022 with a forecast of 7.4 billion in 2028 [28]. Up until 5G, the permanent identifier (IMSI) could be obtained by any third party [25]. Together with the large transmit range of cellular devices, this is a prime candidate for localization.

Wi-Fi Wi-Fi is another well established technology for wireless communication. While modern operating systems randomize the hardware addresses used in broadcasts, they mostly remain constant per network, making it possible to record multiple measurements if a known network can be spoofed [27]. The range is also sufficient, with around 100 meters, and possibly more in Line-Of-Sight conditions [19].

Bluetooth Low Energy While Bluetooth Low Energy (BLE) also has a wide adoption due to its presence in most mobile devices, it has multiple problems in the context of our use case. One issue is the limited range to around 10 meters [19]. Like other technologies, more recent versions of BLE also try to increase the user privacy by regularly changing the address used in the broadcasts, making tracking infeasible if implemented correctly [3].

Other Technologies While other technologies for medium to long range communications exist and might be applicable to searches, they have not seen widespread adoption in mobile devices. This includes low-power, low-bandwidth protocols such as LoRaWan and SigFox, but also satellite based protocols such as Starlink or Apple's "Emergency SOS via Satellite".

2.4 Related Work

The localization of mobile devices in SAR missions has already been studied in the literature. Albanese et al. [1] introduced an automated solution for SAR missions using UAVs called SARDO (Search-And-Rescue DrOne-based solution) in 2021. The main use case of SARDO is to find victims of natural disasters who cannot communicate with rescue teams because they are trapped beneath rubble. The authors of SARDO claim to be the first ones to provide a cellular SAR solution using drones, that can accurately localize missing persons' mobile phones. They use a concept they call pseudo-trilateration, where only a single UAV is used to estimate the user position. To process the distance measurements and predict future target positions, the authors use machine learning methods like neural networks. The SARDO authors assume that the target mobile phone is close enough to the UAV such that it can be identified and the pseudo-trilateration algorithm can start estimating the target position right away. In contrast, this paper considers entire SAR missions, where initially only a search area is known.

Compared to cellular solutions, other papers discuss different technologies. Schedl et al. introduced an automated SAR method using airborne optical sectioning, which makes it possible to find people with the camera of the drone and imaging techniques, even in occluding forests [24]. The method by Schedl et al. dynamically computes the flight path of the drone, depending on hints from a classifier, that suggest that a missing person might be hidden in a specific region. Like SARDO, Schedl et al. only use a single drone for their solution.

Ha et al. enhance the single-drone approach by introducing a search algorithm suggesting a hierarchical approach with two drones operating at different heights [15]. The drone flying at a high altitude performs a rough search of a larger area and then, based on a probabilistic search algorithm, suggests a smaller region for the drone flying at a low altitude to search. Flying at a high altitude allows the first drone to search a large area quickly, while the low altitude of the second drone allows for a precise search. The probabilistic search algorithm divides the area into smaller regions and assigns probabilities to them, thereby indicating the likelihood of finding the target within that region.

3 Simulation Model

This section introduces the four strategies for automated localization using drones. First, the drone movement patterns of the four strategies are explained. Then, the evaluation methods are described, which are used to evaluate and compare the four strategies. The description of the different types of drones and the selection of the most suitable ones for SAR missions can be found in the Appendix A.

3.1 Search Strategies

In the following, the four strategies are introduced. They all cover the period of time from the takeoff of the first drone until the precise localization of the target via trilateration. The input of the search algorithms is always the size, shape, and location of the search area. The search area can be found via proximity-based localization. If the algorithms do not fail, the output is a target location estimate. The strategies vary in their focus on either minimizing cost or minimizing the time necessary to locate the target and maximizing the success rate. Furthermore, they differ in the information that is assumed to be given, as the third strategy introduced takes advantage of the knowledge about the target's start position.

Each strategy uses a total of three drones of different types. At the beginning of the search mission, only one or two drones, depending on the strategy, are sent out to search the whole area. The four strategies mainly differ in this period of time until the first identification of the target. Once the target has been identified, the rest of the drones are called for the trilateration phase. In this stage, the strategies all use the flight patterns described for the naive strategy. These flight patterns cope with the mobile target escaping or evading the drones during trilateration.

Naive Strategy The naive strategy forms the base for all four strategies. It uses one drone to find the initial search area, called the catcher drone, and two additional drones for trilateral localization in the next step. The catcher drone is selected to be a single-rotor drone, while the other drones are multi-rotor drones. The single-rotor drone has a very high flight range and endurance due to its possibility to be powered by fuel, therefore it is able to search large areas, e.g. an entire rural mobile radio cell. The multi-rotor drones then only have to fly for shorter amounts of time, since their target area is delimited drastically from the whole search area to the identify range of the catcher drone. Their task could also be performed by single-rotor drones, but since a shorter flight time and less payload are sufficient during the precise localization, the less costly multi-rotor drones are chosen. After the target is initially found, the single-rotor drone acts as one of the three drones necessary for trilateration.

For an efficient search of the area by the catcher drone, the area needs to be covered by circles with minimal overlapping. This is called the circle covering problem [2]. Fejes [10] proved in 1942 that the densest way of packing circles is in a hexagonal lattice, where the centers of the circles coincide with the centers of the regular hexagons and the radii are equal to the radii of the inscribed circles of the hexagons. According to [18], this approach can also be used for circle covering, but for the covering problem the circles do not inscribe, but instead circumscribe the hexagons. To find the points the drone has to visit, a hexagonal grid is used and the centers of the hexagons overlapping with the search area are selected. The drone heads for the centers of the hexagons by means of shortest distances, in a row-by-row manner. The first hexagon visited is the one closest to the current position of the UAV. This way, the entire area is searched very quickly and with almost minimal redundancy. Figure 1 illustrates the movement of the first drone along the hexagonal grid, simulated as a Python Matplotlib animation [29].

Once the catcher drone finds the UE, it keeps hovering at its current position and then calculates its distance to the UE. Now, the location of the UE can be narrowed down to a point on the circle around the catcher drone with its distance to the UE as radius. The second and third drone, the multi-rotor drones, are then called to the area around the catcher drone. They circle the catcher drone such that the entire area formed by its search radius is covered. In order to avoid getting the same result twice from both the second and third drone, one of them circles the catcher drone clockwise, and the other one counter-clockwise, so the target is approached from different directions. Once they detect the UE, they calculate their distances to the UE, similarly to the first drone. The position of the UE can then be estimated to be at the intersection of the three circles. For the estimate to be as accurate as possible, the distance measurements should be taken at the same time or shortly after one another, especially if the target is moving quickly, such that they are not outdated when calculating the circle intersection.

If the catcher drone was not able to find the target UE in its first round searching the area, because the target evaded the drone, the drone goes back to the first hexagon and visits all of the hexagon centers again, until the UE is in its reach. As long as the target is within reach of a drone, the drone is hovering. Since the distance between the hovering drone and the moving target might be changing, the distance has to be recalculated and updated constantly.

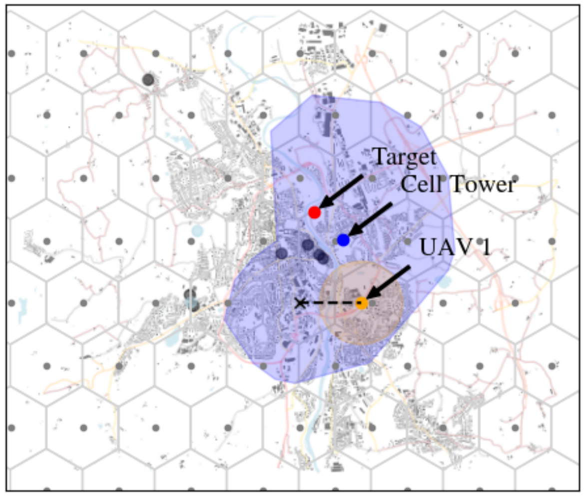


Fig. 1: Movement of the catcher drone (orange dot) along the hexagonal grid (gray). The transparent orange circle shows the identify range of the drone and the blue polygon depicts the search area. The dashed line indicates the direction of the drone towards the black cross.

If the target moves out of the reach of a UAV before the trilateration could be performed, the drone has to stop hovering and resume its search.

There are two cases to be distinguished: In the first case, one drone loses the target, but it is still in the reach of another drone. Then, the UAV that lost connection circles the other one until the target UE is back in its reach. In the second case, none of the drones have the target in their reach. In this case, the drones position themselves on a circle around the position of the drone which lost the target last. The idea behind this strategy is to cover all of the directions where the target could have escaped to. If the UAVs are too slow and not able to perform measurements on the target again, they start moving outward, away from the position where the target was last seen.

Figure 2 illustrates the movement of the drones in case two: First, the drones gather around the former position of the drone which had the target in its reach last. This position is marked as x_1 in Figure 2. The dashed arrows show the movement of the drones and the dashed circles are their identify ranges. Secondly, they move outwards, if the target remains lost. This is depicted with the solid arrows and circles, showing the new position of the drones. As soon as one of the drones finds the target again, the remaining drones circle the one which has the target UE in its reach, as in case one. If the different kinds of drones have varying search radii, the smallest radius determines the distance at which the three drones surround x_1, the former position of the drone which lost the target last. The maneuvers that are performed in the cases where one or more drones lose sight of the target are independent of the search area and can therefore also be used if the target leaves the area after it was found by at least one drone at some point.

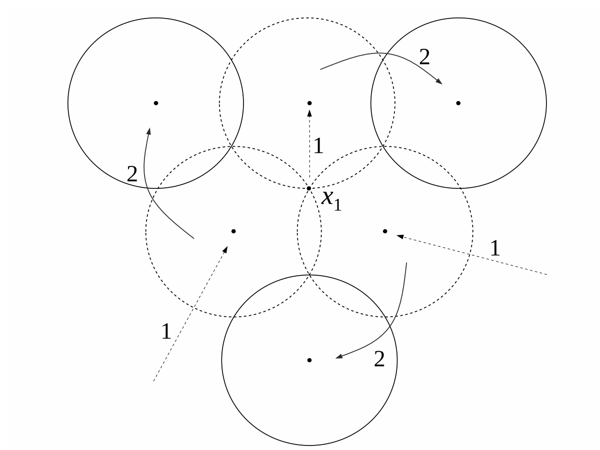


Fig. 2: Drone movement in the case of the target being lost by all three drones. x_1 marks the former position of the drone which lost the target last. First, the drones gather around x_1 (1) and then, if unsuccessful, they move outwards (2).

Strategy with Two Catcher UAVs Compared with the naive strategy, the strategy described in this section uses a second catcher drone for the initial part of the search, i.e. to make the first contact with the target device. The reason for using only one single-rotor drone in the naive strategy was minimizing the cost of the drones and their equipment. Therefore, at first only one drone was sent out to find the rough position of the target UE. This strategy, on the other hand, aims at being fast rather than cost-efficient. The purpose of the second catcher drone is to cover more ground at once and quickly search the area for the target UE. Once one of the catcher drones was able to find the target, only one additional multi-rotor drone is necessary for trilateration, since two UAVs are already airborne. Therefore, the total number of drones does not increase compared to the naive strategy. However, the equipment is more expensive and now two drones are required to have a high endurance and to carry large payloads.

The strategy for the initial search of the area is still based on a hexagonal grid, where the centers of the hexagons that are overlapping with the search area are visited by the catcher drones. The second catcher drone visits the centers in reverse order compared to the first catcher drone. Besides covering the search area up to twice as fast compared to the naive strategy with one catcher drone, depending on the starting points of the drones and their distances to the search area, it is also harder for a moving target to evade two UAVs coming from different directions than just a single one. Once one of the catcher drones finds the target, the second UAV takes on the role of a multi-rotor drone as in the precise localization step of the naive strategy and the third drone is called to aid in the trilateration. Both the second catcher drone and the multi-rotor drone circle the catcher drone that has found the target first. In this stage of the localization mission another advantage of the strategy with two catcher drones can be discovered: Since the catcher drone, which was not able to find the target first, is already in the search area and closer to the target than it was during launch, it can reach the other catcher drone much more quickly than a multi-rotor drone with the same start position in the naive strategy. This also reduces the risk of the target getting away while the second and third drone are still approaching.

The cases where one or more drones lose sight of the target are very similar to the naive strategy. If at least one drone still has the target in its reach, it is circled by the other drones. If the target was found by a catcher drone and then manages to escape all three drones, the position of the drone which had contact to the target UE last is surrounded as shown in Figure 2. Assuming that the search radius of a catcher drone is larger than of the smaller drones joining for trilateration, this strategy provides more drones with a higher coverage compared to the naive strategy, also making it less likely to lose contact to the target.

Strategy with Known Target Start Position The motivation of this strategy is that additional information leads to assumptions about the target position at the beginning of the mission and can be used to improve the drone movement and find the target more quickly. This additional knowledge could e.g. come from the person reporting the target missing at the police station.

In order to take advantage of the additional knowledge of the missing person's start position, the naive strategy is adjusted. The catcher drone which is sent out first immediately visits the hexagon which overlaps with the search area and contains the known target start position. From there, it continues its search, visiting the other hexagon center points in the same row-by-row manner as in the naive strategy. The drone approaches the hexagon center point instead of directly heading for the target start position, because it is assumed that the exact coordinates of the start position are not given and the target might have moved already when the person is reported missing. Furthermore, this allows for a smooth transition into the naive strategy. The other drones perform the same maneuvers as in the naive strategy.

If the target is assumed to be moving on streets because it is travelling by bike or car, this strategy might also improve the mission time until the target is found. Areas with a high street density or highly frequented crossroads can be chosen as a start position for the search. In the simulation, this use case is not considered explicitly.

Random Strategy Besides the strategies based on a hexagonal grid for the movement of the first (two) drone(s), a strategy based on random search paths is also introduced. In this strategy, the naive strategy is altered such that the catcher drone moves towards random positions in the search area instead of following a hexagonal lattice. Once it reaches such a random position, the next one is chosen. The rest of the strategy remains the same.

The random strategy has no memory in the sense that it can be sure to visit every position in the search area. However, it could be advantageous over the other strategies, if the first UAV heads for the center of the area right away and can take advantage of the whole identify range of the UAV from the beginning instead of following hexagons at the rim of the search area in order to cover it entirely.

3.2 Evaluation Methods

The strategies are evaluated based on different aspects: probability of success, duration, and cost. Besides the evaluation of the differences between the strategies, the effect of parameter changes like target movement speed and drone identify range on the results are also studied. Furthermore, different search area shapes and sizes are investigated.

Probability of Success The SAR mission can fail for various reasons. Those reasons are divided into two groups: The UAV-specific reasons and insufficient accuracy.

The group of UAV-specific reasons for failure are caused by characteristics from the hardware specifications of the UAVs chosen for a strategy. If one or more of the drones run out of power before the target is successfully located, the mission is considered a failure. Therefore, the cases in which a mobile target might evade or escape the drones have to be considered. If a drone can run out of power in a mission with an immobile target, the strategy needs to be adjusted. This issue could be addressed with changes in the flight maneuvers, start positions of the drones closer to the search areas or the choice of a more durable drone type.

The accuracy is measured in meters and describes the distance between the true location of the UE and the estimated location. It mainly depends on the localization method that is chosen, the LOS conditions, and the parameter that is chosen for the localization method, e.g. RSS or ToA, and their resolution. The accuracy of the strategies is not investigated with the simulation and has to be tested with experiments.

Mission Time Duration refers to how fast the missing person's UE can be located. The start of a mission is defined to be the takeoff of the first UAV and the end is either when the target is successfully located or when the mission is interrupted, e.g. because of an empty battery or tank. Interrupted missions are not considered for mission time calculations.

Mission Costs Cost considers the acquisition cost of equipment such as the UAVs and the technical equipment they are carrying as well as operating costs like electricity or fuel cost for the time of the search mission or maintenance and personnel costs. Therefore, cost also depends on the duration of the mission.

Table 1 summarizes the acquisition and operating costs of multi-rotor and single-rotor drones. The values are explained in detail in the Appendix B. The comparison shows that the acquisition costs of single-rotor drones and of their equipment in a SAR use case as well as the operating costs of single-rotor UAVs are significantly higher than of multi-rotor drones. On one hand, since especially the energy cost is dependent on the duration of the search mission, longer missions and therefore also flight times are expected to cause higher expenses. On the other hand, the use of more single-rotor drones, which might cause shorter mission and flight times, also causes higher expenses than the use of multi-rotor drones, due to the high acquisition costs and the higher energy costs per minute.

Table 1: Comparison of the costs of a multicopter with a single-rotor UAV. The single-rotor UAV is assumed to carry five SDRs.

	Multi-Rotor	**Single-Rotor**
Acquisition Cost in k Euro		
UAV	3-3.6	15-180
Equipment	2.14	10.7
Operating Cost in k Euro / year		
Maintenance	90	120
Energy (in cents/min.)	0.45	1.82

4 Simulation Results

This section presents the simulation results. First, the simulation assumptions and parameters are introduced. To evaluate the performance, the target speed, the UAV identify range and the scenario are varied. The scenario includes different search areas with varying shapes, sizes, and drone station positions. The performance of the strategies is discussed in comparison with each other.

4.1 Simulation Assumptions and Parameters

In order to evaluate and compare the strategies introduced in this paper, they are simulated as Python Matplotlib animations [29]. For each parameter set, the animation runs 1000 times to generate 1000 samples of a Monte Carlo simulation. In order to ensure the comparability between the four strategies, the same seed values are used for the target start positions and movement of the target across the four strategies. The strategies are tested in two dimensions, but can easily be expanded to three dimensions, if the ground is considered the fourth surface necessary for multilateration in three dimensions.

The drones are assumed to be placed on the roofs of public buildings like police stations or fire departments, such that they can start their missions autonomously at any time. To download and display the geospatial data of the search areas, the OSMnx Python package was used [6]. The OSMnx package allows to download street networks from OpenStreetMap as graphs.

The simulation is based on localization via cellular technologies and the cooperation of the service provider is assumed. Table 2 shows simulation parameters that are specific to the technical equipment. The speed chosen for the drones is not their maximum airspeed, but instead their cruise speed, which they can keep up for longer periods of time. The maximum airspeed is only used when the drones run out of power and have to return to their station quickly. The identify time is the time it takes for the equipment to identify the target, once it enters the range of a drone. Depending on the technology used for localization, it can be significantly higher for the first identification. The maximum flight times are assumed to be half an hour for the multi-rotor drones and four hours for the single-rotor drones.

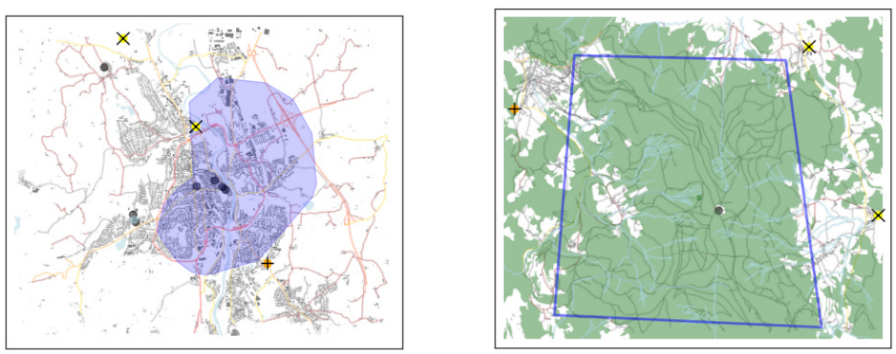
Table 2: Assumed UAV simulation parameters for the two-step strategies.

UAV Type	**Speed**	**Identify Time**	**Max. Flight Time**
Multi-Rotor	17 m/s	5 s	30 min
Single-Rotor	16 m/s	30 s	240 min

Since it is necessary to get a permit to fly a drone at a height greater than 120 m in the EU [13], the UAVs are assumed to fly at a constant height of 120 m, although this does not apply to security authorities [14]. At a large height, the identify range of the drones is bigger than at a small height. At the same time, assuming the authorities still need to register drones that are flying at a high altitude, getting a permit before flying the drones in a SAR mission can cause a considerable delay. Therefore, we assume the maximal height allowed without a permit. The control range of the drones is assumed to be large enough such that all flight maneuvers are possible. The UAVs are assumed to have access to correct information about their own geographical locations at all times during the mission. The distance measurements are assumed to reflect the true distances, without non-LOS disturbances and measurement inaccuracies.

The two scenarios used for the performance evaluation are shown in Figure 3. The scenario on the left, Figure 3a, shows a mobile radio cell in Kempten. In this scenario, the cell of the cell tower the missing person's device is connected to determines the search area. The cell ID of the serving base station is assumed to be disclosed by the service provider after a request made by the authorities

[5]. Kempten is a city in southern Germany close to the Alps. It was chosen as an example in this paper to stress the use case of a missing hiker that could be located with the help of UAVs. The approximate value of the cell area size can be found in Table 3. Figure 3b shows a different map section. It shows an area of woodland in the mountain range “Bayerischer Wald” between St. Englmar on the top left and Achslach on the right. This scenario was chosen to show the functionality of the search strategies in a larger area with bad cell coverage. Instead of searching a mobile radio cell for the mobile phone of a missing person, the drones search the woodland where the missing person is known to be with a high probability, e.g. because they were planning to go hiking there and did not return from their trip. Since there is no cell to be plotted in Figure 3b, the search area is indicated with a blue line. In this scenario, the area to be covered by the drones is about three times larger than in the mobile cell scenario.



(a) Mobile cell scenario

(b) Woodland scenario

Fig. 3: Search areas and UAV start positions of the two scenarios. The blue polygons show the search areas and the black crosses in yellow circles and the black plus signs in orange circles mark the UAV start positions of multi-rotor and single-rotor UAVs, respectively.

Besides the search areas of the different scenarios, Figures 3a and 3b also show the UAV start positions. The black plus signs in orange circles show start positions of single-rotor drones and the black crosses in yellow circles show the ones of multi-rotor drones. In the case of the strategy with an additional catcher drone, the second catcher drone starts at the northern fire department in the Kempten scenario and at the fire department in Achslach on the bottom right in the woodland scenario. The individual as well as the average distances between the UAV start positions and the centroids of the areas are summarized in Table 3. The UAVs start from different positions, such that they are spread over a larger area and can assist in missions in other search areas as well.

Table 3: Search area shape and size scenarios used for the simulation, with the distances between the UAV start positions and the search area centroid.

Scenario	Mobile Cell	Woodland
Search Area Size	26.2 km^2	77.8 km^2
Distance UAV 1	3.17 km	6.71 km
Distance UAV 2	6.34 km	6.81 km
Distance UAV 3	2.35 km	6.80 km
Average Distance	3.95 km	6.77 km

In addition to the two scenarios, varying target speeds and UAV identify ranges were tested. The target speeds are chosen to represent different means of transport, specifically walking (2 m/s) and biking (7 m/s). The most important speed values for SAR missions are the small ones, because they are related to the use cases of missing hikers, disoriented or elderly people who were reported missing. The target is assumed to select a random destination position and head for the selected position at a constant speed until the destination is reached. It then (randomly) selects its next destination. If the target moves at a speed of at least 7 m/s, it has to use streets.

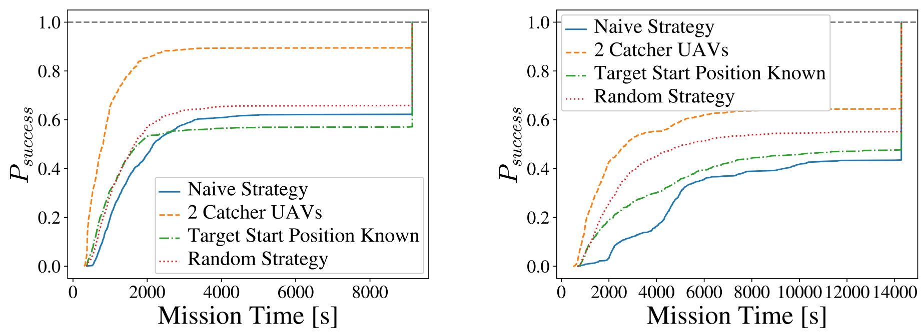
In order to test the compatibility of the strategies with different technical equipment with varying transmission powers, the UAV identify range values are varied. If the target is within the identify range of a UAV for a sufficient period of time, it can be identified by the equipment on the drone. Table 4 shows an overview over the values. Since the equipment carried by the single-rotor drones is assumed to have a higher transmission power and therefore a higher range than the smaller equipment on the multi-rotor drones, the multi-rotor range values were chosen to be approximately the single-rotor values divided by $\sqrt{2}$. Next to varying choices of technical equipment, the different UAV identify range values can also represent bad weather conditions or different drone heights. In rainy weather, the identify range might go down [17]. When the drones fly at a higher altitude and the transmission power is high enough, they might cover more ground at once [15]. Halving the identify range of the single-rotor UAV from 1000 m to 500 m quarters the area covered by the UAV at one moment in time. The same relation is also true for the multi-rotor drone. In the mobile cell scenario, the cell area is approximately 26.2 km^2. At a range of 1000 m / 700 m, the three UAVs can cover up to 23.7% of the cell area at once. Lowering the range to 500 m / 350 m leads to only 8.8% of the cell being covered, if the UAV ranges do not overlap and lie fully inside the cell.

4.2 Performance Comparison

This chapter presents the results of the Monte Carlo simulations regarding the success rates and the time it takes until the target is found.

Table 4: UAV identify range values used for the simulation.

Radio Characteristics	**Medium Gain**	**High Gain**
Single-Rotor	500 m	1000 m
Multi-Rotor	350 m	700 m



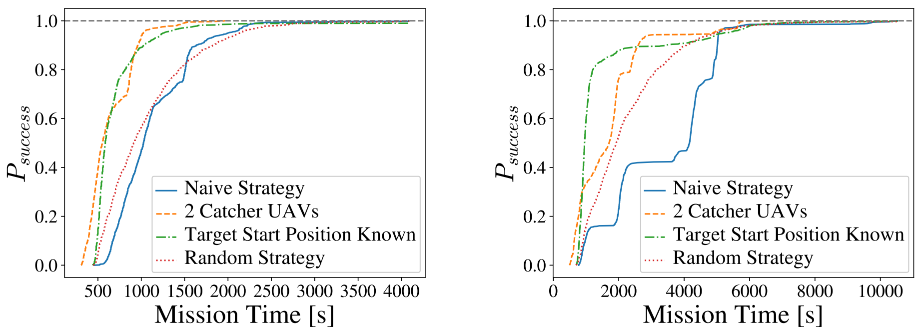
(a) Mobile cell scenario

(b) Woodland scenario

Fig. 4: Performance comparison of the strategies in the two search area scenarios. The target speed is fixed to 7 m/s and the UAV identify range to 1000 m / 700 m.

Scenarios Figure 4 shows the performance of the strategies in the two scenarios. The probability of failure and speed of varying configurations are depicted together in the form of cumulative distribution function (CDF) plots. The ticks on the x-axis show the mission time in seconds and the y-axis shows the probability of success. The mission time values of the failed missions are set to a value higher than the longest successful mission. Therefore, the total success probability can be read from the graph right before all of the lines jump to a success probability of 1. The rest of the graph shows, which configuration is more likely to lead to a fast success. The graphs with higher success probabilities at lower mission times show the better speed results. Since the takeoff time of the multi-rotor drones, which are mainly responsible for failed missions because of empty batteries, depends on the point in time when the single-rotor drone first identifies the target, failed missions can vary in their mission times. Furthermore, searching for a longer time does not necessarily increase the chances of finding the target, since it might have left the search area, becoming unlikely to find.

The target speed is fixed to 7 m/s and the UAV identify range is 1000 m / 700 m. The strategy with an additional catcher UAV (orange) is the best strategy regarding success probability and speed, in both of the scenarios. The results of the other three strategies appear close to each other, especially in the mobile cell scenario. In the woodland scenario, the random strategy clearly is the runner-up regarding its success probability (red).



(a) Mobile cell scenario

(b) Woodland scenario

Fig. 5: Performance comparison of the strategies in the two search area scenarios at a lower target speed. The target speed is fixed to 2 m/s and the UAV identify range to 1000 m / 700 m.

However, the strategy with known target start position (green) shows more completed missions at an earlier point in time in the mobile cell scenario. The strategy with known target start position appears to result in less mission time needed to find the target, but at the same time in a lower success rate than the one of the naive strategy. In the woodland scenario with a search area which is three times as large than in the mobile cell scenario, the random strategy (red) clearly shows a better performance than the other strategies with only one catcher drone. In this scenario, the strategy with known target start position (green) shows a clear improvement compared to the naive strategy.

Target Speed When the target speed is reduced to 2 m/s, improved performance results can be observed across all strategies. Figure 5 shows an improvement of the success probability to up to 100% when decreasing the target speed to 2 m/s. In the case of a standing target with a speed of 0 m/s, the results are not displayed in the figure but were very similar. The strategy with known target start position (green) benefits the most from the lower target speed. Its success probability is almost doubled from approximately 50% at 7 m/s to 100% at 2 m/s and the mission duration is now comparable with the two catcher drone strategy (orange), which used to be the best strategy in this scenario. Both strategies are now able to find the target in 1000 seconds (17 minutes) in 90% of the cases, while the naive and random strategies take around 1700 seconds (28 minutes). In a scenario with an immobile target, the random strategy performs the worst out of the four strategies.

At 7 m/s, the strategy which is using two catcher drones from the beginning is the only one with a reasonable success rate (around 90%). This is displayed in Figure 4a. At even lower target velocities, if the target is standing or walking, all strategies reach excellent success rates. However, the strategy with two catcher drones and the strategy with known target start position show better mission time values. If the target start position is not known and only one catcher drone is available, the naive strategy is a good substitute.

The woodland scenario also has much better success rate results at lower target velocities. Figure 5b shows, that even in a scenario with such a large search area, the success rate can be improved to almost 100%, if the target is moving at 2 m/s. In more than 90% of the cases, the target could be found with the strategies with two catcher drones and with known target start position in up to 2500 seconds (42 minutes), with the random strategy in up to 4000 seconds (67 minutes) and with the naive strategy in up to 5000 seconds (83 minutes). These values are much higher than in the mobile cell scenario (Figure 5a) and it therefore takes all of the strategies longer to find the target in a bigger area, even at low target speed values. Figure 5b shows that in this configuration, the strategy with known target start position is clearly faster than the strategy with two catcher drones and the naive strategy shows the worst performance.

UAV Identify Range Decreasing the UAV identify range leads to the strategy with known target start position being pushed to the bottom together with the naive strategy, as shown in Figure 6. The strategy with an additional catcher drone (orange) shows the best performance out of all four strategies in all UAV range configurations, but does not achieve a success rate of more than 50%. Therefore, for the strategies to be of use in a SAR scenario, high identify range values need to be ensured.

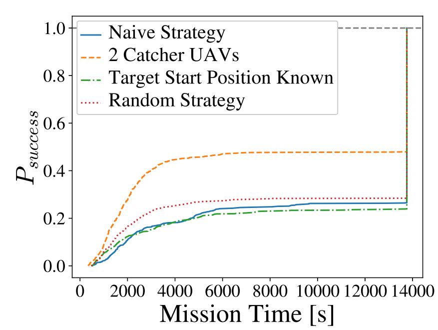


Fig. 6: Performance of the strategies with a UAV identify range of 500 m / 350 m. The search area is the one of the mobile cell scenario and the target speed is 7 m/s.

4.3 Comparison of the Strategies: Summary

The results regarding the comparison of the energy costs of the strategies can be found in the Appendix C. The discussion shows that the strategy with two catcher drones can make up for the higher energy costs per minute by finding the target quicker. Comparing the strategies using only one catcher drone, the fastest and most successful ones are also the ones with the lowest energy costs.

To sum up, the success of the automated localization of a missing person's mobile device using UAVs depends on many parameters. One of the parameters, which has a big impact on the success rate and the time necessary to locate the target, is the target velocity. Under the simulation assumptions, the strategies show very promising results in the use cases of a missing hiker or an elderly person who wandered off. In those cases, if cost is secondary, the strategy with two catcher drones performs best. If the start position of the target is known, the corresponding strategy performs just as well and can be used to save acquisition costs. In the woodland scenario, it performs even better than the strategy with two catcher drones. Otherwise, if the target start position is not known and costs still have to be considered, the naive strategy also leads to good results, at the expense of the target not being found as quickly. In most of the cases, the target is found after half an hour. If the target is riding a bike, the only strategy with reasonable success rates is the strategy with two catcher drones. At even higher target velocities, the strategies are not reliable enough and cannot be applied.

The second parameter, which needs to be considered, is the identify range of the UAVs. It is crucial for the success of a search mission to use equipment with a high transmission power, such that the area covered by the UAVs is large. The size of the search area has a big impact on the time necessary to find the target.

Therefore, not only the success of the search mission depends on the given search area and parameter configuration, but also the selection of the most fitting strategy.

5 Conclusion

The search for missing persons proves difficult, especially in terrain that is hard to reach. Since there might only be a small period of time available to find the person unharmed and healthy, the authorities are under a lot of time pressure to find them. In order to support the authorities in such matters and make SAR missions faster, more efficient and more successful, this paper introduces four intuitive strategies for the automated localization of missing persons' technical devices using UAVs. The introduced strategies are evaluated with extensive simulations considering various scenarios and parameters. The results show that, in the case of a standing or walking target, the strategies are able to find the target with almost 100% certainty. They mainly differ in the time necessary to find the missing person and the necessary investments to buy the equipment. The strategy with two catcher UAVs could even find the target in more than 80% of the samples at a faster target speed. The random strategy also showed unexpectedly good results, especially compared with the naive strategy in many scenarios. Based on these results, the best suited strategy for a certain scenario can be selected.

The simulation framework is particularly designed to develop novel optimized search strategies for given real-world scenarios. This can be used to optimally plan the number of drones and their launch locations for an expected number of SAR missions or to perform on-the-fly mission planning. As future work, we plan to integrate an engine to generate and evaluate strategies based on evolutionary algorithms in real-time to provide increased mission planning capabilities.

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A Selection of UAVs

Unmanned aerial vehicles (UAVs), more commonly known as drones, are aircrafts without human pilots onboard [21]. According to [32], UAVs can be categorized into the four major types multi-rotor, single-rotor, fixed-wing, and fixed-wing-multi-rotor hybrid.

During the localization, the UAVs need to be able to visit certain points in the search area and hover at those points in order to take measurements. While flying, the drones need to carry varying technical equipment, depending on the technology used for localization and the task of the drone. Especially the drones deployed for the beginning of the search until the first identification of the target have to be able to fly for a longer time. In the next step, the search area is already delimited and the more precise localization can be performed much quicker. This is when the additional, smaller drones are used. There is no special need for very fast drones, since they have to scan the environment while flying and might even miss UEs if they pass by them too quickly.

Multi-rotor UAVs or multicopters are the most popular type of drone. The name usually specifies the number of rotors: Tricopters have three rotors, quadcopters, the most common multicopters, have four, those with six propellers are called hexacopters and octocopters have eight [32]. Multicopters are easy to manufacture and therefore the cheapest option. Furthermore, they can be controlled without special training necessary, they are agile, can hover, and are capable of vertical take-off and landing (VTOL) [21]. The biggest drawback of multicopters is that, on average, they can only fly for 20 to 30 minutes. This is due to the large amount of energy that is spent on stability in the air [32]. Multi-rotor drones are able to carry some payload, but the flight time is reduced with the amount of payload that is attached. Multi-rotor UAVs are therefore well suited for the task, but limited in their flying time.

Single-rotor drones resemble small helicopters. They have one large propeller at the top, which is lifting the drone into the air, and one small propeller at the tail, which is used for steering. Single-rotor UAVs can hover, are agile, are capable of VTOL, can fly for long times when powered by fuel or gas and carry heavy payloads. Because of the large rotor blades, single-rotor drones can be dangerous and their operation requires skill. Unlike the multi-rotor UAVs, single-rotor drones are expensive [32,26]. They are very robust and durable, while the possible flight patterns are similar to those of multi-rotor drones. If the flying time of multi-rotor drones is too short to identify the target, a single-rotor drone would be a fitting replacement. The multi-rotor drones can then be added for the precise localization, since they are more compact, cheaper and less dangerous than single-rotor drones, because their rotor blades are not as large.

Fixed-wing drones have wings and look like small airplanes. They are fast, built to fly long distances and stay airborne for a long time, if necessary for hours. One of the disadvantages of fixed-wing drones is their limited agility. They are not capable of hovering or VTOL and can only move forwards. Furthermore, there is a lot of space necessary for launch and recovery. The person flying the fixed-wing drone needs to be trained, and the drone itself is expensive, too [26]. Since fixed-wing UAVs cannot hover and their position is constantly changing, it is not possible to use them for taking measurements.

The fixed-wing-multi-rotor hybrid drones have propellers as well as wings and can hover, glide and are VTOL-capable, if not yet perfectly, since they are still in development [32,26]. The hybrid UAVs have very high endurance, range and speed [32]. To sum up the choice of UAVs, multi-rotor and single-rotor drones are selected to perform the tasks in the four strategies.

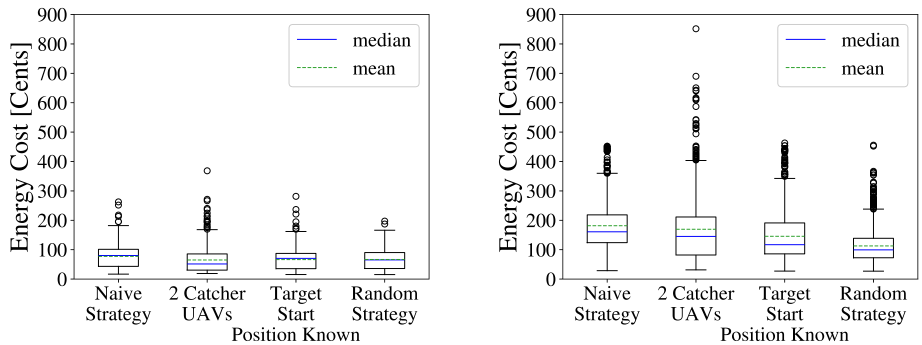
B Acquisition and Operating Costs

The costs for the UAVs and the equipment they are carrying are considered separately in this paper. Dileep et al. name a price range between 5 and 6k AUD for multi-rotor drones, which corresponds to around 3-3.6k euros, and a price range between 25 and 300k AUD for single-rotor drones, which corresponds to approximately 15-180k euros [8].

To provide numbers for the cost of the technical equipment carried by the drones, positioning in cellular networks is assumed. In this case, the multi-rotor drones can be carrying the USRP B210 board by National Instruments, which costs approximately 2.14k euros together with the steel enclosure kit, neglecting the cost of the antennas [22]. While the smaller multi-rotor drones only carry a single SDR, the larger drones have to carry multiple ones to efficiently search the radio spectrum for the device signatures.

According to Fritzsch et al., the operating costs of drones include energy and maintenance costs [11]. The cost of the maintenance of a multi-rotor drone found in the literature, 90k euros per year, is very significant [11]. The authors claim that the reason for this is that the maintenance of the drone is offered by the manufacturer and paid for in the form of a monthly service fee of 7.5k euros. Alternatively, an employee could be trained to maintain the drones. Then, the personnel costs together with the cost of the spare parts might be less than the 90k euros/year [11]. Since the single-rotor drone is more expensive than the multi-rotor drone, it is assumed that the spare parts of the single-rotor drone are also more expensive, which contribute to a higher maintenance cost.

The multi-rotor drone is assumed to carry two flight batteries with 274 Wh of energy each. Assuming electricity costs of 25.65 cents/kWh for retail [4], fully charging both batteries would cost 14.06 cents. With two fully charged batteries, the drone can fly for 31 minutes. It is assumed that the power consumption is steady during the whole flight of the drone and the electricity cost can be assumed to be 0.45 cents/minute. It is assumed that the single-rotor drone has a fuel tank that can hold up to eight liters of fuel. With a full tank, the UAV can



(a) Mobile cell scenario (b) Woodland scenario

Fig. 7: Comparison of the energy costs per mission of the strategies in the two search area scenarios. The target speed is fixed to 7 m/s and the UAV identify range to 1000 m / 700 m. The blue, solid line is the median and the green, dashed line the mean.

fly for up to four hours. Assuming a price of 54.74 cents per liter of kerosine [30], fully refuelling the drone would cost 437.92 cents. If the power consumption of the drone is steady, the energy cost can be assumed to be 1.82 cents/minute.

C Energy Cost Comparison

This section compares the energy costs of the four strategies in varying search area configurations. For the comparison of the costs, successful missions as well as failed missions are considered. Failed missions cause energy costs just like successful missions and since in failed missions the drones keep flying until one of them runs out of battery or fuel, also considering failed missions works as a punishment for strategies with a bad success rate in the comparison.

To display the distributions of the energy costs over the simulation samples, Figure 7 uses boxplots. For each sample, the flight time of every UAV is multiplied with the energy cost per minute, depending on the type of UAV. The blue, solid line of the plot shows the median of the resulting cost samples and the green, dashed line shows the mean. The boxes are limited by the first (lower) and third (upper) quartiles of the samples. The vertical lines, the whiskers, extend to the data points within 1.5 times the interquartile range, which is the difference between the values of the first and third quartiles. The circles mark the outliers.

Comparing the energy costs of the strategies in the four scenarios, the costs of the strategy with two catcher drones are surprisingly close to the costs of the other strategies. Figure 7 displays that in the mobile cell scenario, the median of the strategy with two catcher drones is even lower than of the other strategies. This shows that the time savings of this strategy are able to cancel out the higher energy costs per minute of the additional catcher drone. However, the strategy with two catcher drones shows a high number of outliers, which makes it harder to predict the energy costs of this strategy. In the woodland scenario, the energy costs are approximately doubled. Here, the random strategy results in the lowest energy cost value. The only strategy, which had a higher success rate than the random strategy in the woodland scenario, was the strategy with two catcher drones. In this scenario, the speed of the strategy with two catcher drones cannot make up for the higher energy costs per minute. Furthermore, the number of outliers is very high across all four strategies.

Especially at low target speed values (0 m/s and 2 m/s), which are not displayed in the figures, the strategy with known target start position is the least costly strategy. At 0 m/s, this strategy also shows almost no variance, since almost all targets are found immediately.